



Predictive modeling for port retro-area management: future scenarios for strategic Brazilian ports

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ABSTRACT

Brazil hosts some of the most important ports in Latin America that represent key logistical cargo distribution for both national and international trades. The need for modernizing port infrastructure is a pressing issue for improving Brazilian logistic optimization, which includes accommodating larger vessels with greater cargo capacity, and has driven sustained investment in the sector. These investments have focused on expanding operational areas including storage, customs processing, maintenance, and distribution, as well as on the construction of new berths and logistics centers, to reduce bottlenecks, logistics costs, and enhancing port competitiveness. This study focuses on eight of the main ports in Brazil, selected based on their size, cargo throughput, and economic relevance, while also ensuring spatial representation along the Brazilian coastline. A spatial analysis is conducted for the period 2000–2022 within a 10 km buffer around each port, in order to assess land use and land cover (LULC) changes in the period and feed a predictive model to deliver scenarios for the next decade. The simulations for 2032 are developed under two scenarios. The first represents a trend based projection, while the second incorporates territorial and environmental constraints, including indigenous lands, marron territories, speleological heritage areas, and legally protected environmental areas such as federal and state conservation units. These constraints are applied either totally or partially, depending on the level of legal protection and the regulatory framework established under current Brazilian legislation. The premise of finding significant differences in the future pattern of land use occupation when contrasting the socio-environmentally conservative scenario with the scenario governed by the trend of continuous territorial transformations was not fully satisfied. The results indicate differences between the two scenarios. In addition, some ports exhibit physical constraints to expansion, either due to the full occupation of available land or their proximity to urban and industrial areas. This finding suggests that future port capacity growth will depend less on immediate port back-land expansion and more on the development of inland infrastructure, implying increased investment in intermodal transport systems.

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1. Introduction.

Brazilian ports play a central role in facilitating both national and international trade, acting as key nodes in global supply chains. Over the past decades, Brazil has experienced renewed economic growth driven by agribusiness exports, reindustrialization efforts, energy transition investments, and the

strengthening of South – South trade relations (Rožić et al., 2016), (Pimenta, 2025). This expansion has intensified the demand for efficient logistics systems, placing increasing pressure on port infrastructure (Oliveira et al., 2013). Despite significant public and private investments in transport systems including highways, railways, airports, and ports. Brazil continues to face persistent logistical bottlenecks, commonly referred to as the "Brazilian Logistic Cost" (Cullinane; Bergqvist; Wilmsmeier, 2012).

Recent investments reflect the strategic importance of the sector. In 2024, federal transport investments reached approx-

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imately R\$ 24 billion, while concession programs mobilized nearly R\$ 160 billion (ANTAQ, 2025). Port modernization initiatives have also injected substantial resources into port complexes, including targeted investments in the South and Southeast regions aimed at improving infrastructure, expanding access, and strengthening port – city integration (ANTAQ, 2026), (Oliveira et al., 2013). Nevertheless, infrastructure expansion has not kept pace with increasing trade demand, vessel upscaling, and the growing need for stronger hinterland integration. As a result, ports continue to operate as critical bottlenecks within Brazil's logistics system (Cullinane; Bergqvist; Wilmsmeier, 2012).

In response to these pressures, port activities are progressively extending beyond their formal boundaries into surrounding back-land areas, driven by intermodal integration, the development of logistics platforms, and industrial expansion (Pizzolato; Scavarda; Paiva, 2010), (Rožić; Rogić; Bajor, 2016). Considering this, the hinterland emerges as a key component of port performance, encompassing logistics systems, transport integration, and inland infrastructure such as dry ports, terminals, and distribution centers (Cullinane; Bergqvist; Wilmsmeier, 2012), (Silva, 2016). Port competitiveness increasingly depends on the efficiency of these connections, as intermodality enables cargo to travel longer distances and expands the functional reach of ports (Costa et al, 2022), (Shayan and Mohabbati - Kalejahi, 2026), (Sdoukopoulos & Boile, 2020). At the same time, vessel upscaling has reduced unit transport costs, reinforcing the concentration of flows through major ports while increasing the importance of efficient inland distribution (Pizzolato; Scavarda; Paiva, 2010).

These dynamics have intensified competition among ports, as different ports may share overlapping hinterlands and compete to attract cargo flows beyond their immediate areas of influence (Sdoukopoulos & Boile, 2020). While the hinterland can be conceptually understood as a continuous area located behind the port, in practice it is dynamic and constantly reshaped by infrastructure development, connectivity, and logistics strategies (Pizzolato; Scavarda; Paiva, 2010), (Silva, 2016), (Gattuso; Cassone; Pellicanò, 2023).

However, port development does not occur uniformly and often generates significant spatial and socio-environmental challenges. Coastal port regions frequently experience pressure on environmentally protected areas, infrastructure deficits, and unplanned urban expansion. Informal settlements and socio-spatial inequalities may intensify in these areas, increasing vulnerability and land-use conflicts (Oliveira et al., 2013). These processes have direct implications for land use and land cover (LULC), often resulting in the conversion of natural ecosystems and agricultural land into industrial and urban uses. While such transformations support economic development, they also generate environmental degradation and social challenges (Cullinane; Bergqvist; Wilmsmeier, 2012).

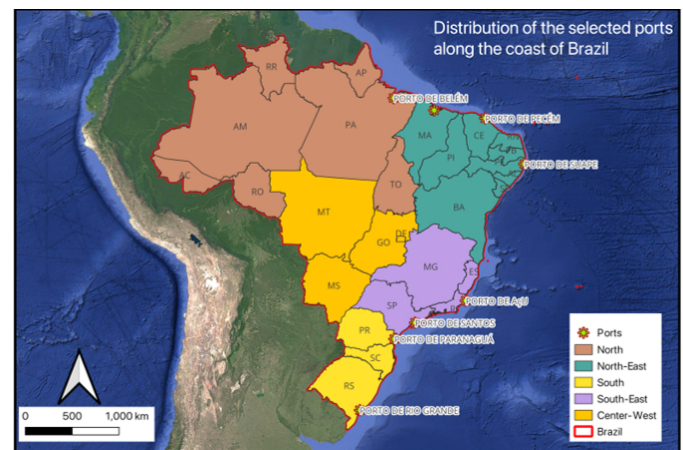
Despite the importance of these dynamics, integrated studies combining high-resolution spatial data with territorial and logistical analysis remain limited in Brazil. This study addresses this gap by analyzing the spatial dynamics of Land Use and Land Cover (LULC) in the surroundings of the eight major

Brazilian ports between 2000 and 2022 and simulating future expansion scenarios for 2032 under different regulatory scenarios, in order to assess constraints and opportunities for port expansion and their implications for logistics and territorial planning.

2. Study Area.

Brazil is the country that has the largest spatial extension in Latin America and it is divided in 5 regions as is shown in figure 1. To ensure spatial representativeness across the Brazilian coastline, this study selected a set of eight Brazilian main important ports based on criteria such as size, cargo throughput and economic relevance to ensure spatial representativeness across the Brazilian coastline. The selected hubs include Belém in the North; Itaqui, Pecém and Suape in the Northeast; Açú and Santos in the Southeast; Paranaguá and Rio Grande in the South. These ports are critical logistics nodes for commodity exports, industrial complexes, and containerized cargo, and play a strategic role in supporting Brazil's recent export growth and infrastructure expansion agenda. Other than the logistic perspective, the choice of these 8 ports also considered the geographic context in order to capture environmental and socioeconomic diversities.

Figure 1: Location of the 8 strategic Brazilian ports along the coast.



Source: Authors.

A summary of the characteristics for the eight ports is shown in table 1.

3. Methodology.

The methodology is structured into six main steps, as illustrated in Figure 2. The primary data source consists of Map-Biomass Collection 9 for the years 2000, 2010, and 2022, considering a 10 km buffer to each port. Google Earth Engine (GEE) was used to access and download the datasets, which were subsequently processed in QGIS. Python was employed to compute the transition and confusion matrices, as well as to

Table 1: Main port characteristics of the selected Brazilian ports.

Port	State (Brazil)	Region (Brazil)	Year of Inauguration	Main Cargo	Volume (2022) (million tons)	Extension (Ha)	Type of Location
Belém	Pará (PA)	North	1909	General cargo	4.5	182	River
Itaquí	Maranhão (MA)	North	1972	Bulk / fuels	13.2	510	Estuarine
Pecém	Ceará (CE)	Northeast	2002	Bulk / containers	22.8	1,350	Open Ocean
Suaípe	Pernambuco (PE)	Northeast	1983	Bulk / containers	23.7	17,300	Open Ocean
Açu	Rio de Janeiro (RJ)	Southeast	2014	Oil / gas - bulk	26.9	13,000	Open Ocean
Santos	São Paulo (SP)	Southeast	1829	Containers / bulk	162.4	7,800	Estuarine
Paranaguá	Paraná (PR)	South	1935	Bulk	55.1	418.67	Estuarine
Rio Grande	Rio Grande do Sul (RS)	South	1915	Bulk	49.3	5,560	Estuarine

Source: Authors.

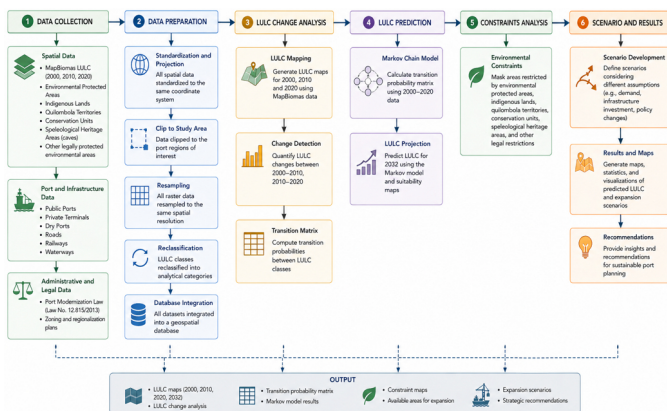
Table 2: LULC classes used for image classification.

Class Name	Class
Vegetation	1
Farming	2
Sand	3
Urban	4
Mining	5
Other Non Vegetated Areas	6
Water	7

Source: Authors.

analyze changes in land use areas across different classes over time.

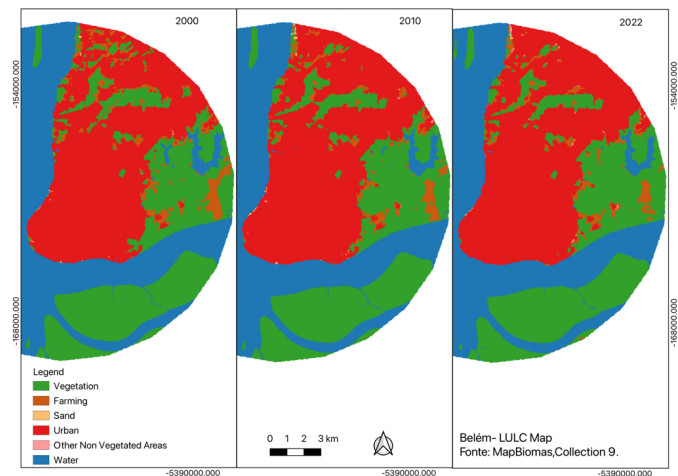
Figure 2: Description of the methodology applied divided in six steps.



Source: Authors.

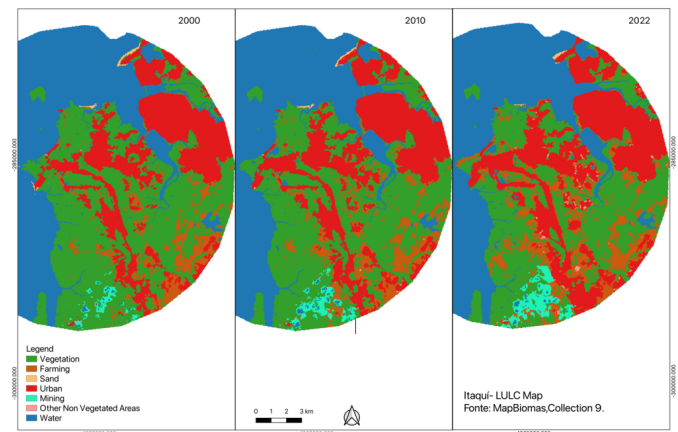
Every image was exported with a spatial resolution of 30 meters and a common and official geographical reference system (EPSG 4674: SIRGAS 2000) ensuring spatial comparability across the analyzed port areas. MapBiomas, Collection 9 has already classified the images, in their own categories. For the purpose of this study, the images obtained were reclassified in Qgis to group the original classes into seven thematic categories of interest as shown in table 2. Based on this reclassification, the areas occupied by each class were calculated considering the periods 2000–2010, 2010–2022, and 2000–2022 view figures 3–10.

Figure 3: Spatiotemporal dynamics in observed Land Use and Land Cover in Belém between 2000 and 2022.



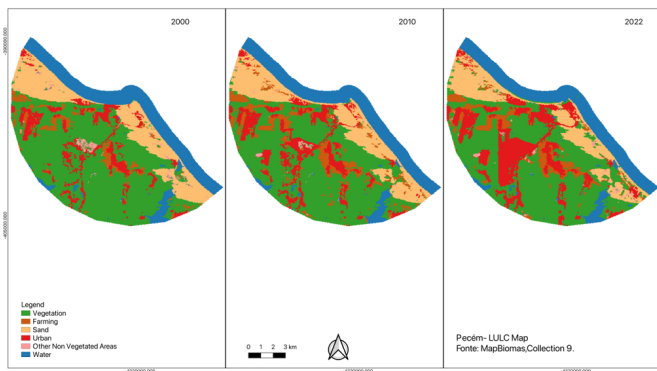
Source: Authors.

Figure 4: Spatiotemporal dynamics in observed Land Use and Land Cover in Belém between 2000 and 2022.



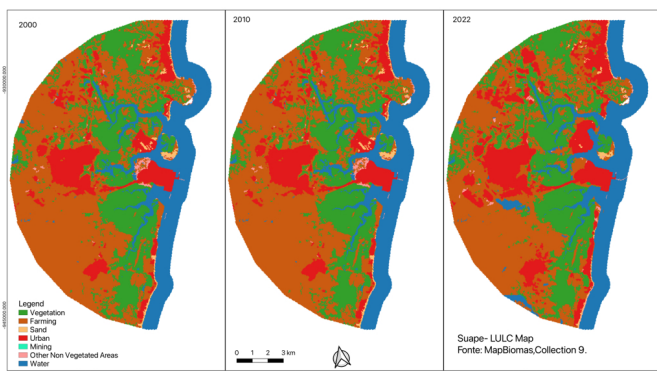
Source: Authors.

Figure 5: Spatiotemporal dynamics in observed Land Use and Land Cover in Pecém between 2000 and 2022.



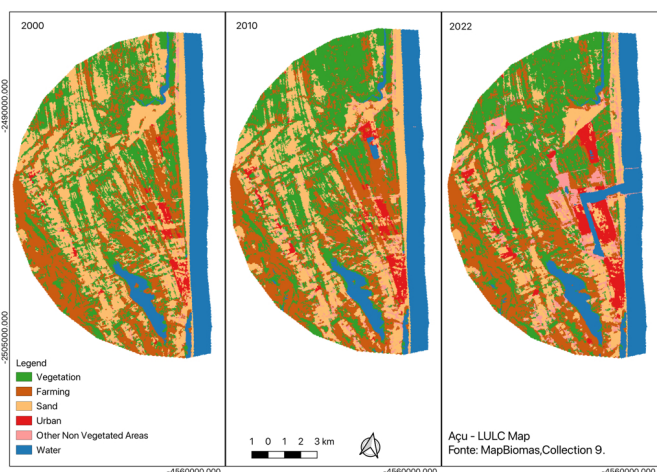
Source: Authors.

Figure 6: Spatiotemporal dynamics in observed Land Use and Land Cover in Suape between 2000 and 2022.



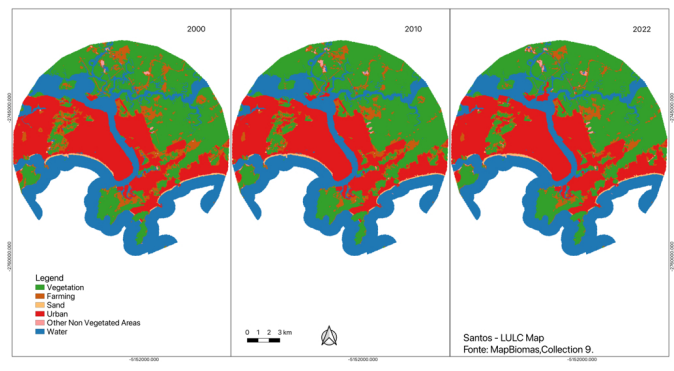
Source: Authors.

Figure 7: Spatiotemporal dynamics in observed Land Use and Land Cover in Açu between 2000 and 2022.



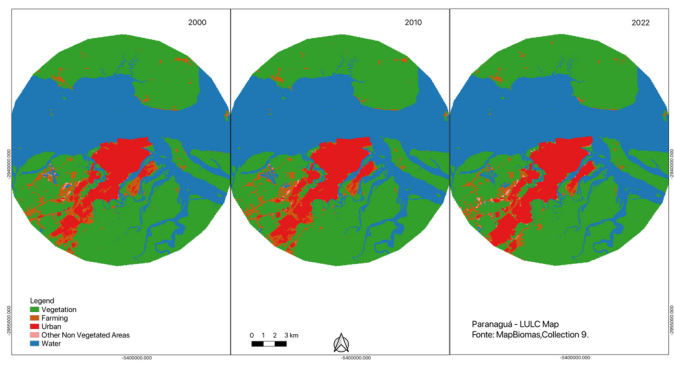
Source: Authors.

Figure 8: Spatiotemporal dynamics in observed Land Use and Land Cover in Santos between 2000 and 2022.



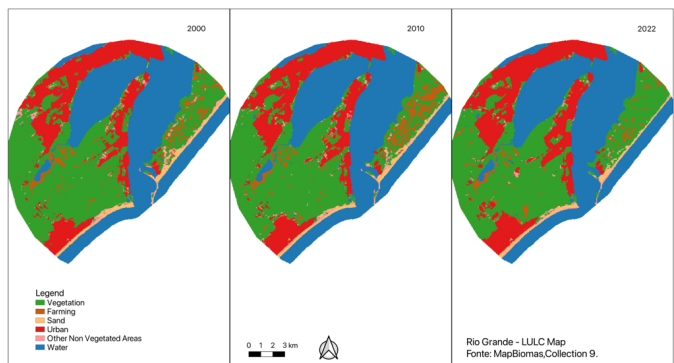
Source: Authors.

Figure 9: Spatiotemporal dynamics in observed Land Use and Land Cover in Paranaguá between 2000 and 2022.



Source: Authors.

Figure 10: Spatiotemporal dynamics in observed Land Use and Land Cover in Rio Grande between 2000 and 2022.



Source: Authors.

For this study, modeling and projection of land use and land cover changes were done using a Markov chain based approach. First, transition matrices were constructed from 2000 and 2010 raster datasets to estimate the probabilities of change between different land use classes. Within the Markov framework, these matrices represent the likelihood that a given land

cover class will transition to another over time, assuming that future changes depend on the current state and the observed transition probabilities. Using these transition probabilities, a simulation of land use and land cover for the year 2022 was generated. The reliability of this simulation was then assessed by comparing it with the actual 2022 raster through a confusion matrix, which measures the agreement between simulated and observed data. The model achieved strong predictive performance as shown in table 3. The satisfactory validation results indicated that the Markov-based model was capable of accurately reproducing observed spatial patterns. These results also revealed a high level of agreement between simulated and observed land-use patterns, supporting the robustness of the modeling framework.

Table 3: Classification accuracy assessment: overall accuracy and Kappa coefficient.

Accuracy	Kappa coefficient
0.61 - 0.96	0.50 - 0.93

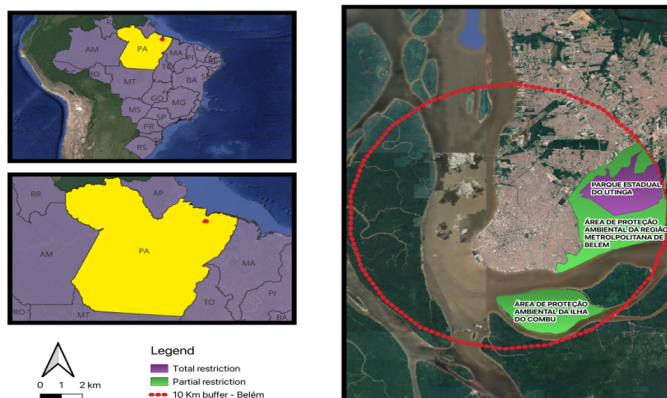
Source: Authors.

Based on this validation, a new simulation for the year 2032 was produced using updated transition matrices derived from the 2010 and 2022 datasets. This step ensures that the projection reflects more recent land use dynamics while maintaining consistency with the Markov modeling approach.

The study employed a spatially explicit modeling framework combining: Transition matrices to quantify historical land-use changes (2000-2022) and Weights of Evidence (WoE) to estimate spatial transition probabilities. The restrictions are shown in figures (11 -18) and were considered as follows:

- Partial restriction: Environmental Protected Areas.
- Total restriction: Indigenous Lands, Quilombola territories, speleological heritage areas (caves), and legally protected environmental areas such as Conservation Units.

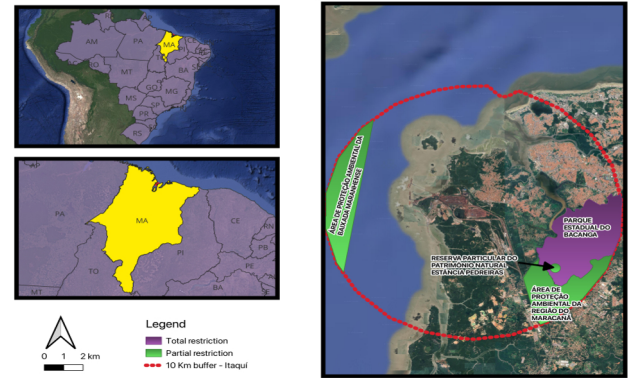
Figure 11: Spatial distribution of environmental constraints around the port of Belém.



Source: Authors.

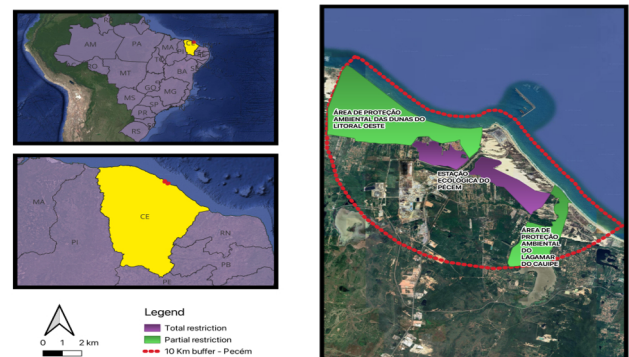
The shapefiles for the restrictions were obtained from the Instituto Chico Mendes de Conservação da Biodiversidade (ICM-BIO), Fundação Nacional dos Povos Indígenas - Governo Federal (FUNAI), Instituto Brasileiro de Geografia e Estatística (IBGE), Infraestrutura Nacional de Dados Espaciais (INDE).

Figure 12: Spatial distribution of environmental constraints around the port of Itaquí.



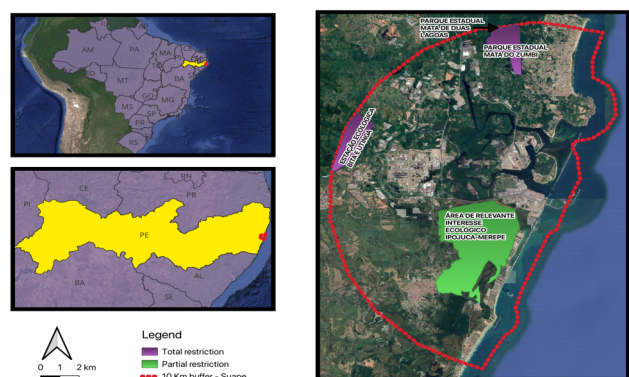
Source: Authors.

Figure 13: Spatial distribution of environmental constraints around the port of Pecém.



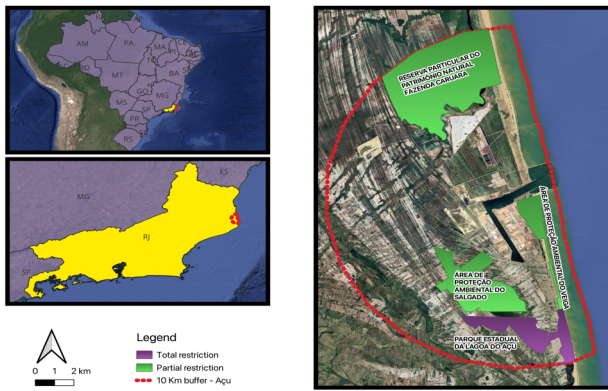
Source: Authors.

Figure 14: Spatial distribution of environmental constraints around the port of Suape.



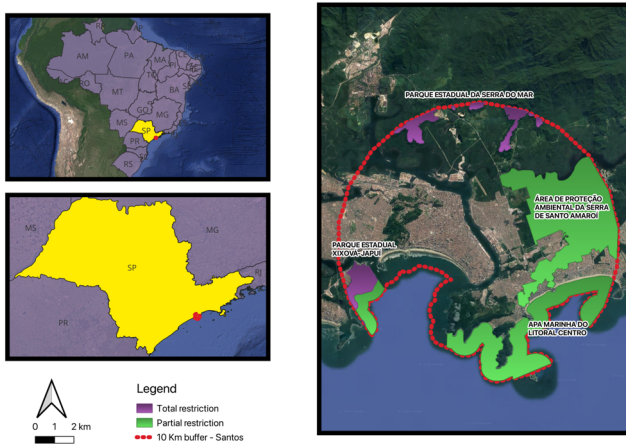
Source: Authors.

Figure 15: Spatial distribution of environmental constraints around the port of Açú.



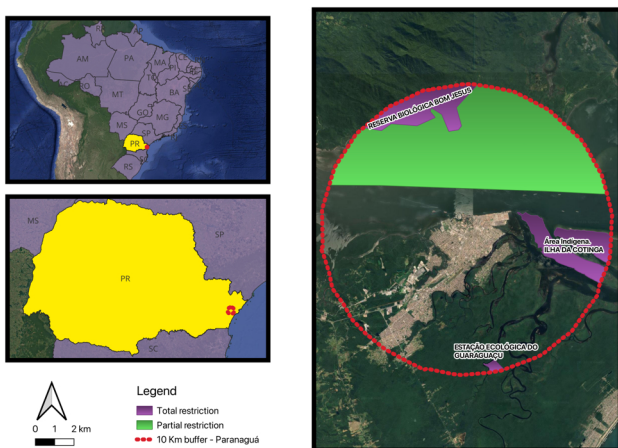
Source: Authors.

Figure 16: Spatial distribution of environmental constraints around the port of Santos.



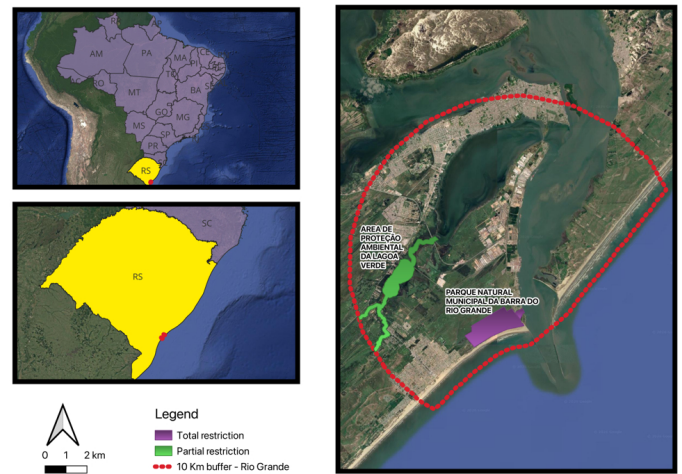
Source: Authors.

Figure 17: Spatial distribution of environmental constraints around the port of Parangará.



Source: Authors.

Figure 18: Spatial distribution of environmental constraints around the port of Rio Grande.



Source: Authors.

Two simulation scenarios were developed in order to see results:

Scenario 1: Trend-Based Expansion. This scenario simulates land-use changes based solely on historical transitions observed between 2000 and 2022, without considering regulatory or environmental constraints.

Scenario 2: Policy-Oriented Restricted Expansion. This scenario incorporates partially or fully spatial constraints, depending on the legal protection level defined under Brazilian legislation.

Restrictions were applied as either total or partial, depending on the level of legal protection and regulatory framework established under current Brazilian legislation.

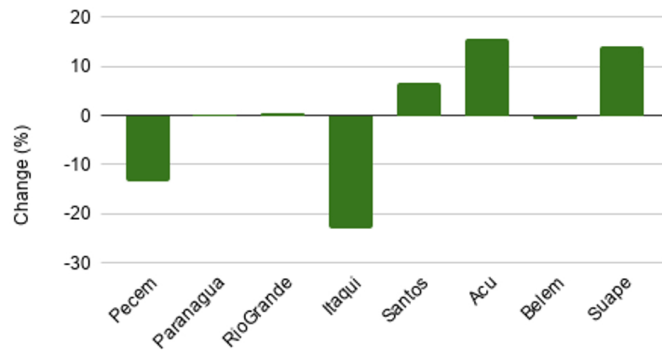
4. Results.

The model delivers a CSV file containing the tabulation of the transitions of the classes across the study periods. The area (in hectares) for the years between 2000 and 2022 is presented in figures (19-25). The script also provides a CSV file with the results of the differences between both scenarios: Trend-Based Expansion and Policy-Oriented Restricted Expansion.

Between 2000 and 2022, the most affected land-use classes were Urban and Farming areas. The most significant changes were observed in the retro-area of the Port of Suape, where farming land decreased by approximately 2570 ha, while urban areas increased by approximately 2200 ha, reflecting rapid industrial and logistics expansion. Water-related changes also showed contrasting patterns. In the Port of Santos, water surface decreased by approximately 360 ha during the same period. In contrast, the Port of Açú showed a water surface increase of approximately 390 ha, associated with port construction and infrastructure development initiated around 2014.

Figure 19: Percentage of change in Vegetation class for each port through the period of study.

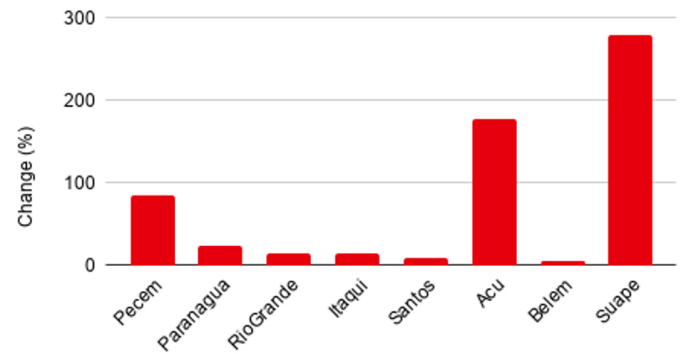
Vegetation change from 2000 to 2022



Source: Authors.

Figure 22: Percentage of change in Urban class for each port through the period of study.

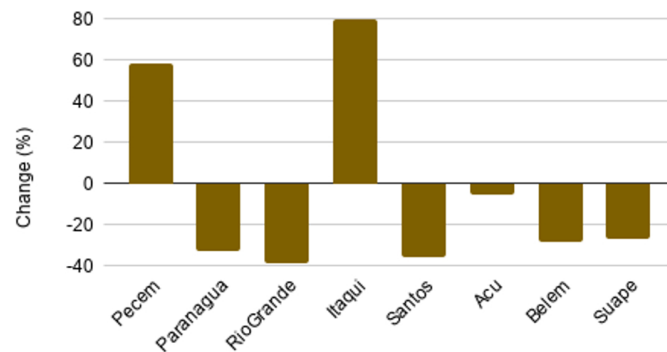
Urban change from 2000 to 2022



Source: Authors.

Figure 20: Percentage of change in Farming class for each port through the period of study.

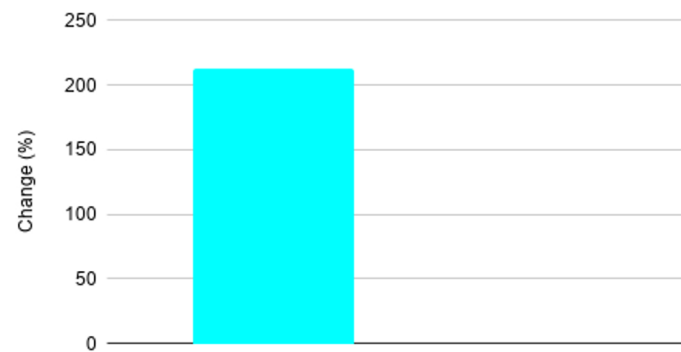
Farming change from 2000 to 2022



Source: Authors.

Figure 23: Percentage of change in Mining class for each port of Itaquí through the period of study.

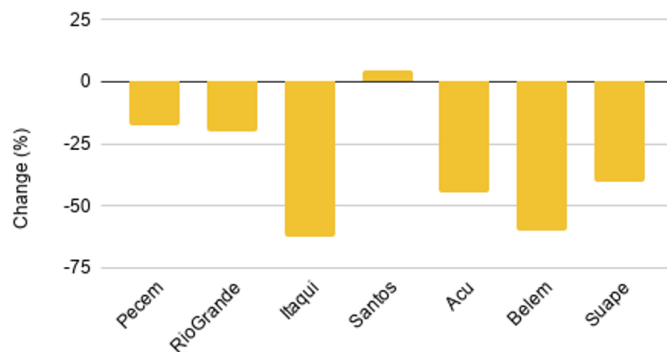
Mining change in Itaquí from 2000 to 2022



Source: Authors.

Figure 21: Percentage of change in Sand class for each port through the period of study.

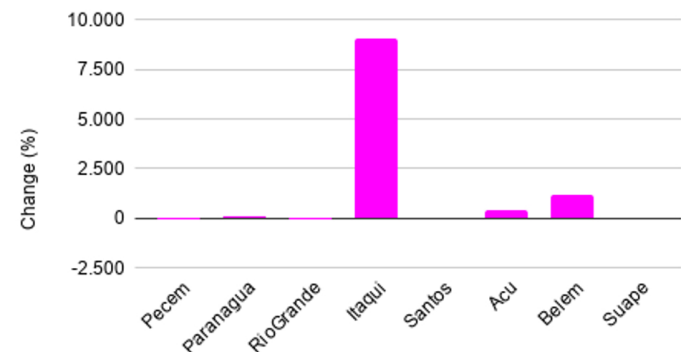
Sand change from 2000 to 2022



Source: Authors.

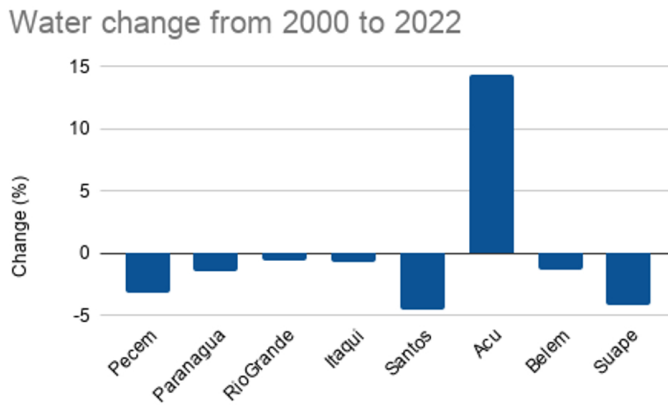
Figure 24: Percentage of change in Other Non Vegetated Areas class for each port through the period of study.

Other Non Vegetated Areas change from 2000



Source: Authors.

Figure 25: Percentage of change in Water class for each port through the period of study.



Source: Authors.

Future scenario simulations for 2032 revealed that policy-oriented restrictions can play an essential role to urban and industrial expansion in most port back land areas, particularly in rapidly expanding logistics hubs.

Figure 26 shows the differences between the simulation with no constraints and the simulations with the constraints applied. Since the values were calculated as the difference between simulation with no restrictions and simulations with restrictions (scenario 1 - scenario 2), positive values indicate that each class decreased after applying the restrictions, whereas negative values indicate an increase under restriction scenario. It means that the restrictions increased vegetation class for almost all the ports except for Açú. Sand class has increased also in Açú, Pecem and lightly in Itaquí and Rio Grande. Farming class has also raised but just for the ports of Açú, Suape and a shortly in Belém.

Urban class and farming are the ones that stand out the most after the restrictions specially for Itaquí and Pecém. These ports reflects main impacts compared with the other ports. More mature port systems, such as Santos, Paranaguá, and Rio Grande, showed smaller differences between scenarios, suggesting higher territorial stability and consolidated land-use structures.

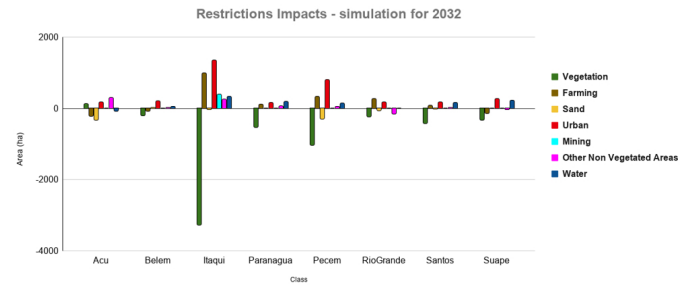
However, results indicate that policy interventions tend to redistribute land-use pressure rather than fully eliminate expansion trends, as evidenced by localized increases in agricultural, vegetated areas or mining in some regions. Mining class is present only in two ports: Itaquí and Suape, but for this analysis between 2000 to 2022, the change in Suape remain in 0, so the changes are observed just for the port of Itaquí.

According to the simulation results for 2032, the Port of Itaquí is projected to experience the most significant changes among the analyzed ports. The results indicate a substantial loss of vegetation area, which is primarily converted into urban expansion, agricultural activities, and mining areas.

Similarly, the Port of Pecém also exhibits notable land use transformations, characterized by a reduction in vegetation and sandy areas, accompanied by an increase in urban land and agricultural activities.

More consolidated port systems showed smaller differences

Figure 26: Simulation of the impact caused by the environmental restrictions implemented in the Brazilian ports.



Source: Authors.

between scenarios, indicating greater territorial stability, limited space for further expansion within their immediate retro-port areas and mature land-use structures. As a result, their development tends to shift toward inland cities that offer greater availability of land for storage and logistics operations. This outward expansion facilitates the integration of port management with broader distribution networks, enabling the extension of their hinterlands.

5. Discussion.

The results reveal that port expansion is a driver of land-use transformation in Brazil, particularly in emerging logistics hubs. The conversion of agricultural and natural areas into industrial and urban land reflects broader structural changes in the Brazilian economy.

The comparison between scenarios highlights the importance of regulatory frameworks in shaping spatial outcomes. While environmental and territorial constraints can significantly reduce undesirable expansion, they may also shift pressures to less regulated areas. This suggests that policy interventions must be integrated and multi-scalar, combining environmental protection with economic planning and infrastructure development. Furthermore, the relatively small differences observed in mature port systems indicate that early-stage planning is crucial. Once land-use patterns become consolidated, the capacity for intervention decreases significantly. Although the model demonstrated strong predictive performance, further improvements can be achieved by incorporating additional spatial drivers, such as:

- Trade volumes
- Infrastructure accessibility
- Transport integration
- Urban expansion pressure
- Socioeconomic indicators

6. Conclusion.

The model demonstrated to be robust to run large datasets, the predictive framework successfully reproduced historical land-use dynamics and provided robust future projections under different planning scenarios. Port territorial management must be predictive rather than reactive, and spatial modeling tools are essential to strengthen societal capacity to anticipate and mitigate future land-use conflicts.

This study provides a comprehensive analysis of land-use dynamics in Brazilian port back land area, combining historical data and predictive modeling to assess future expansion scenarios. The results demonstrate that port expansion is a key driver of territorial transformation, with significant environmental and socio-economic implications. Although policy constraints can mitigate some impacts, they often redistribute pressures rather than eliminate them. Finally, sustainable port development in Brazil requires a shift from reactive to predictive planning, supported by spatial modeling tools and integrated policy frameworks. This approach is essential to balance economic growth with environmental protection and long-term territorial resilience.

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