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Spatio-Temporal Dynamics and Land Degradation Vulnerability in Northeastern Rio de

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Abstract

Land degradation remains a critical challenge in Brazil, driven by historical deforestation and intensifying anthropogenic pressures. This study presents a geospatial assessment of land degradation risk and conservation priorities in northeastern Rio de Janeiro State, utilizing a modified UNEP-PAP/RAC framework. We integrated very-high-resolution (< 1m) Airbus imagery with multi-temporal Land Use and Land Cover (LULC) data (1985–2024) from MapBiomas to analyze landscape stability and transformation.

Results indicate that while 66.66% of the area is stable, 25.77% is actively degrading, with rill erosion (16.31%) dominating the undulating Northwest Fluminense terrains. The assessment classifies 44.11% of the territory as High Priority, requiring immediate curative measures for eroded pastures and preventive protection for Atlantic Forest and Restinga fragments. The 39-year LULC analysis reveals a profound transition, marked by a 115.8% urban expansion and a 70.6% increase in temporary crops at the expense of traditional mosaic uses and fragile coastal ecosystems. These findings underscore a critical "tipping point" for regional land health and provide a robust scientific basis for integrating geospatial monitoring into sustainable land management policies and municipal planning.

1. Introduction

Land degradation, the persistent decline in the productive capacity and ecological health of land, is a silent crisis unfolding across the globe, driven by unsustainable human activity (IPBES 2018). It is commonly associated with soil erosion, loss of soil fertility, vegetation degradation, and declining land productivity, resulting from the interaction between natural processes and human activities (UNCCD 1994; Bai et al. 2008). While a global challenge, its drivers and impacts are intensely local, shaped by unique geographies and histories. In Brazil, land degradation has become an increasing concern, especially in the southeastern region, where rapid land-use transformation coincides with environmentally fragile conditions. The state of Rio de Janeiro is frequently associated with the lush, humid ecosystems of the Atlantic Forest; however, its northeastern quadrant presents a starkly different environmental reality. The study area is located in this region (Fig. 1) which stretches from the once-lush valleys of the Paraíba do Sul River inland, encompassing areas like Itaperuna and Miracema, across the vast plains of the Northwest Fluminense, and down the Atlantic coast through the municipalities of Quissamã, Carapebus, and the coveted Lakes Region around Cabo Frio and Búzios (INEA 2013). This is a land of transition: from fertile alluvial soils that supported dense forests to sandy coastal plains anchored by fragile restinga (sandbank scrub) ecosystems (Henriques et al. 1986). This region is currently grappling with severe land degradation that threatens the ecological and economic stability of the territory (Soffiati 2011). Historically, this area was the epicenter of Brazil's sugarcane and coffee cycles, which led to the near-total suppression of native vegetation and the depletion of soil nutrients through centuries of monoculture (Castro et al. 2019). In contemporary times, this historical degradation is exacerbated by regional climatic constraints. Research by Bohn (2014) demonstrates that the North and Northwest of Rio de Janeiro possess specific aridity indices that classify them as "dry sub-humid"

zones, making them the most vulnerable areas in the state to desertification. The combination of historical deforestation, as documented by Soffiati (2011), and the climatic susceptibility identified by Bohn (2014) has resulted in a landscape dominated by degraded pastures and abandoned farmlands. Therefore, there is an urgent need to apply modern geomatics in order to maintain and restore these vital natural resources. Numerous studies in southeastern Brazil have applied remote sensing and Geographic Information Systems (GIS) to analyze land-use and land-cover change, vegetation dynamics, and soil erosion risk, highlighting the strong influence of human activities on land degradation processes (Santos et al. 2024; Visser et al. 2019). To address this, the present study adapts the methodology established by the United Nations Environment Programme's Priority Actions Programme/Regional Activity Centre (UNEP PAP/RAC). While the PAP/RAC framework is well-established, its application has been largely confined to semi-arid and Mediterranean contexts (e.g., Sadiki et al. 2012; Mesrar et al. 2015; Yacine et al. 2019; Tahouri et al. 2022; Elbadaoui et al. 2023; Ziadi et al. 2013; Lhoussaine et al. 2024; Elmoutkine et al. 2024). Applying this tool to a humid tropical coastal zone, characterized by heavy rainfall and steep relief, addresses a significant knowledge gap (AlAbed et al. 2025).

This study aims to perform a thorough land degradation risk assessment for the northeastern parts of Rio de Janeiro State study area by integrating remote sensing and GIS techniques. Specifically, it seeks to map and quantify the spatial distribution of stable and unstable land classes, analyze the associated erosion processes, and produce a conservation priority map that combines stability status with degradation risk. Additionally, the research will evaluate land use and land cover changes over the past 40 years. The results will provide a scientific foundation for land management planning, informing soil conservation, ecosystem restoration, and sustainable regional development in one of Brazil’s most environmentally and economically important states.

2. Material and Methods

2.1 Classifying Stable and Unstable Land Units via PAP/RAC Framework

Land degradation was mapped using a modern, very-high-resolution remote sensing approach. The primary data sources comprised the latest available very-high-resolution satellite basemaps with sub-meter accuracy: Airbus imagery (2025) and Esri World Imagery. To maintain spectral analysis consistency and provide a current medium-resolution baseline, a Landsat image from 2025 was also included. Land cover classification was conducted in ArcGIS using the Maximum Likelihood Supervised Classification algorithm. The classification framework followed the established methodological guidance of UNEP-PAP/RAC for coastal area management (PAP/RAC 1997; UNEP-MAP/PAP 2000). Training samples for the supervised classification were developed and iteratively refined through visual interpretation of the very high resolution Airbus and Esri basemaps. This visual refinement against sub-meter imagery was crucial for defining precise Landsat spectral signatures and achieving high classification accuracy in the absence of concurrent field validation.

The classification employed a dual-track approach based on land unit status, separating stable from unstable areas. Stable land units (non-erosion affected areas) were characterized by three main attributes: (1) the dominant land cover/use type (e.g., sandy areas, wetland, unmanaged areas with forest or agricultural potential, managed forest or agricultural areas, mangroves, Herbaceous Sandbank Vegetation); (2) grade of instability risk (0 = no risk, 1 = low, 2 = high, 3 = highest) derived from intrinsic factors; and (3) the primary drivers of potential instability, including topography, geology, vegetation cover, and anthropogenic pressure. Unstable land units (erosion affected areas) were defined by: (1) the dominant erosion process (sheet or rill erosion); (2) the spatial extent of the affected area within the unit (localized: <30%, dominant: 30–60%, widespread: >60%); and (3) a qualitative expansion trend index indicating the dynamic erosion state (0 = stabilizing, 1 = locally expanding, 2 = regionally expanding, 3 = advancing toward irreversibility).

2.2 Multi-Criteria Framework for Conservation Prioritization

To effectively mitigate land degradation across the study area, resources both technical and financial must be directed to clearly identified priority zones. A spatial prioritization approach was employed, using a multi-criteria scoring system to pinpoint land degradation hotspots that require urgent management action. This framework adheres to the methodology of United Nations Environment Programme's Priority Actions Programme/Regional Activity Centre (UNEP/MAP/PAP 2004) and combines biophysical risks with socio-economic drivers that influence landscape stability throughout the area. The assessment utilized fourteen diagnostic variables (Table 1) selected and categorized into actual degradation risk factors (A–E), socio-economic factors (F–I), and land use factors (J–N).

Table 1
Variables and Scoring Matrix for Land Degradation Intervention Prioritization

Variable	Description	Scoring (1–3)
A	Physical instability risk (stable areas)	1 = low, 2 = high, 3 = critical
B	Extent of area affected (unstable areas)	1 = < 30%, 2 = 30–60%, 3 = > 60%
C	Expansion trend of degradation (unstable areas)	1 = local, 2 = widespread, 3 = generalized/irreversible
D	Multiplicator for increased importance (causative agents or degradation process)	1 = none, 2 = increased, 3 = highly increased
E	Influence on adjacent areas	1 = low, 2 = high, 3 = critical
F	Overexploitation	1 = insignificant, 2 = significant, 3 = crucial
G	Rural exodus	1 = insignificant (< 5% population loss), 2 = significant (5–15%), 3 = crucial (> 15%)
H	Land tenure	1 = secure (private/state with management plan), 2 = moderate (communal/uncertain), 3 = insecure (absentee/unclear ownership)
I	Other aggravating socio-economic factors	1 = none, 2 = moderate (e.g., infrastructure pressure), 3 = severe (e.g., conflict-related land abandonment)
J	Value of current land use (local population)	1 = low, 2 = moderate, 3 = high
K	Value of current land use (national policy)	1 = low, 2 = moderate, 3 = high
L	Potential for forestry	1 = low, 2 = moderate, 3 = high
M	Potential for agriculture	1 = low, 2 = moderate, 3 = high
N	Other land use potentials (recreational, industrial, construction)	1 = low, 2 = moderate, 3 = high

Each variable was assigned an impact score ranging from 1 (lowest impact) to 3 (highest impact). Actual degradation risk variables capture the intrinsic stability of land units and the severity of active degradation processes; their impact scores were taken from the land degradation map produced in section 2.1. Variable A (physical instability risk) for stable areas was assigned directly from the stable area code in the resulting land degradation map. Variables B (extent of area affected by a specific degradation process for unstable areas) and C (expansion trend of a specific degradation process for unstable areas) were also assigned directly from the unstable area's codes in the resulting land degradation map. Variable D (multiplicator for increased importance of causative agents for stable areas or for increased importance of a specific degradation process for unstable areas) and Variable E (influence on adjacent areas) were assessed using visual interpretation by overlapping the land degradation map with the ESRI base map to assign the increased risk importance and its influence on adjacent areas. Overexploitation (F) impact score was assessed by overlapping the land degradation map with the ESRI base map. Rural exodus (G), land tenure (H), and other aggravating socio-economic factors (I) impact scores were given the value (1) as the lowest impact. Following PAP/RAC guidelines (UNEP/MAP/PAP 2004), when specific socio-economic data are unavailable, conservative default scores of 1 (lowest impact) are assigned to Variables G, H, and I to avoid overestimating degradation risk. Land use value variables (J–N) were scored based on visual interpretation by overlapping the land degradation map with the ESRI base map to assign the impact score (1 to 3) based on expert judgment supported by knowledge of the study area.

The final composite prioritization scores were then calculated using distinct formulas for stable and unstable areas, reflecting their different underlying risk structures:

- Stable Areas Priority Score: $[(A \times D + E) \times F \times G \times H \times I] + [(J + K) \times L \times M \times N]$
- Unstable Areas Priority Score: $[(B \times C \times D + E) \times F \times G \times H \times I] + [(J + K) \times L \times M \times N]$

The multiplicative structure captures synergistic interactions where multiple high-risk factors amplify each other, while additive components allow for compensatory relationships. The multiplicative structure follows UNEP/MAP-PAP/RAC technical guidelines (UNEP/MAP/PAP 2004), which prescribe multiplicative aggregation for independent risk factors (A–I) and additive aggregation for complementary land valuation components (J–N). The resulting numerical scores were classified into three distinct intervention priority tiers to guide management actions: High Priority: Score ≥ 60, Medium Priority: Score between 21 and 59, and Low Priority: Score ≤ 20. This quantitative framework translates the multi-criteria assessment into a clear, actionable hierarchy for conservation and restoration planning.

2.3 Multi-Temporal LULC Change Detection (1985–2024)

Land Use and Land Cover (LULC) data were sourced from the MapBiomas Project, a Brazilian multi-institutional initiative that generates annual, high-resolution land cover maps using Landsat satellite imagery with a 30 m spatial resolution (MapBiomas 2025). This study analyzed multi-temporal LULC changes at ten-year intervals (1985, 1995, 2005, 2015, and 2024). The raster datasets for these five target years were processed in ArcGIS 10.8 and spatially clipped to the study area's vector boundary to

isolate relevant LULC patterns. Area calculations for each land cover class were performed by aggregating pixel counts and applying the sensor's spatial resolution, with results expressed in square kilometers, hectares, and proportional cover (%) to facilitate cross-temporal and inter-class comparison.

The total official vector area of the study region is 9,543.27 km². The initial raster extraction from MapBiomas yielded a slightly larger area (10,314.13 km²) (a discrepancy of approximately 8.08%). This variation is primarily attributed to the "edge effect" during the spatial extraction process, where partial pixels along complex shorelines and coastal islands are included in the initial count at a 30 m resolution. To ensure geographical accuracy and consistency, all subsequent area calculations and percentages reported in this study are based on the definitive vector-derived area of 9,543.27 km². This approach enabled a precise quantitative evaluation of land cover transitions over the 40-year period.

3. Results

3.1 Assessment of Land Degradation: Nature and Extent

The spatial assessment of the study area reveals a landscape predominantly characterized by stability (Fig. 2), though significant portions are currently affected by active erosion processes. Of the total 9543.27 km² analyzed, 66.66% (6362.8 km²) is classified as stable land (Table 2). Within these stable regions, the largest single category is Managed Areas with Agriculture Use, covering 20.75% (1980.47 km²), followed by Unmanaged Areas with Agriculture Potential at 14.42% (1376.38 km²). Natural vegetation remains a critical component of the stable landscape, with Managed Areas with Forest Use accounting for 10.54% and Herbaceous Sandbank Vegetation (Restinga) covering 8.46% (807.68 km²). Other vital ecosystems, such as Wetlands and Mangroves, occupy 6.02% and 0.21% of the area, respectively.

The spatial distribution of land stability (Fig. 2) follows a distinct West-to-East gradient, closely aligned with the region's topographical and soil characteristics. Stable areas are largely clustered along the low-lying Atlantic coastal strip and the fertile alluvial valleys of the Paraíba do Sul River, where flatter topography naturally resists high-energy runoff. In these zones, the "Managed Areas with Forest Use" form a stabilizing green belt that protects the soil from direct meteoric impact. Furthermore, the Restinga and Mangrove are frequently observed in the sandy corridors of the Lakes Region (Cabo Frio and Búzios) and the municipalities of Quissamã and Carapebus. In these areas, the fragile Restinga vegetation acts as the final line of defense; where this cover is fragmented by anthropogenic pressure, sheet erosion becomes widespread, stripping the thin topsoil layer and threatening the long-term viability of these unique coastal ecosystems.

Table 2
Assessment of Stable and Unstable Land Categories

Area	Code	Land Category Type	Area (km^2)	Area (hec)	Area (%)
Stable Areas	01	Unmanaged Areas with Forest Potential	586.25	58624.50	6.14
	02	Unmanaged Areas with Agriculture Potential	1376.38	137637.50	14.42
	03	Managed Areas with Forest Use	1006.12	100611.50	10.54
	04	Managed Areas with Agriculture Use	1980.47	198046.75	20.75
	07	Herbaceous Sandbank Vegetation (Restinga)	807.68	80767.50	8.46
	08	Mangrove	19.97	1996.50	0.21
	WL	Wetland	574.75	57475.00	6.02
	SA	Sandy Area	11.19	1119.25	0.12
	Total Stable Area		**6362.8**	**636279**	**66.66**
Unstable Areas	L11 L12	Localized Sheet Erosion	12.10	1210.00	0.13
	L21 L22	Dominant Sheet Erosion	215.99	21598.50	2.26
	L31 L32	Generalized Sheet Erosion	675.18	67518.00	7.07
	Total area of sheet erosion		**903.27**	**90326.5**	**9.46**
	D11 D12	Localized Rill Erosion	105.27	10527.00	1.10
	D21 D22	Dominant Rill Erosion	34.79	3478.75	0.36
	D31 D32	Generalized Rill Erosion	1417.52	141751.50	14.85
	Total area of Rill erosion		**1557.58**	**155757.3**	**16.31**

Area	Code	Land Category Type	Area (km^2)	Area (hec)	Area (%)
	Total Unstable Area (Sheet & Rill erosion)		**2460.85**	**246083.8**	**25.77**
Urban			338.50	33849.75	3.55
Water			381.15	38115.00	3.99
Total study area			9543.27	954327.00	100.00

Conversely, 25.77% (2460.85 km²) of the territory is identified as unstable and actively undergoing degradation. This instability is manifested through two primary erosion processes: rill erosion and sheet erosion. Rill erosion is the more dominant threat, affecting 16.31% (1557.58 km²) of the total study area, with Generalized Rill Erosion impacting 1417.52 km² (14.85%). Sheet erosion affects an additional 9.46% (903.27 km²), with Generalized Sheet Erosion being the most widespread form (7.07%). Urban areas and water bodies comprise the remaining 3.55% and 3.99% of the territory, respectively. Geographically, these unstable areas are primarily located in the transition zones between the coastal plains and the interior plateaus. Rill erosion hotspots are heavily concentrated in the undulating terrain of the Northwest Fluminense, particularly on steeper gradients where secondary vegetation has been cleared for pasture, leaving the soil vulnerable to concentrated water flow. Furthermore, sheet erosion is frequently observed in the municipalities of Morro do Coco and Corrego do Ouro.

3.2 Prioritization of Areas for Conservation and Restoration

The prioritization of conservation efforts highlights the urgent need for targeted environmental management (Fig. 3). Based on the PAP/RAC methodology, a significant portion of the territory—comprising both stable and unstable categories—requires intervention, with 44.11% (Table 3) of the total area classified as High Priority (Priority I) for conservation. Specifically, 20.08% (1916.04 km²) is classified as Unstable High Priority, requiring immediate curative measures, while 24.03% (2292.65 km²) is Stable High Priority, requiring strict preventive protection to maintain its current state.

Geographically, these High Priority zones are intensely concentrated in the interior hilly regions of the Northwest Fluminense, visible in the upper and western portions of the study area (Fig. 2). These areas, encompassing municipalities such as Maniva, Morro do Coco, Serrinha, and Corrego do Ouro, coincide with "hotspots" of rill erosion on steeper slopes where pasture expansion has replaced native forest cover.

A total of 35.38% of the region is categorized as Medium Priority (Priority II). This includes 30.90% (2948.47 km²) of stable land and 4.48% (427.43 km²) of unstable land currently undergoing sheet erosion. These areas are primarily distributed along the transitional margins between the coastal plains and the interior highlands, as well as within the sandy corridors of the Lakes Region and the

municipalities of Morangaba and Campos dos Goytacazes. These zones represent a critical "tipping point" where preventive management—such as protecting fragile restinga (sandbank scrub) vegetation—could effectively halt further degradation.

In contrast, 12.96% of the area is classified as Low Priority (Priority III), consisting of 11.73% (1118.95 km²) stable and 1.23% (117.37 km²) unstable land. These areas are largely found across the low-lying Atlantic coastal strip and the alluvial plains of the Paraíba do Sul River, mainly in the coastal areas of Quissamã and Itabapoana. While these regions are currently the most stable, they remain under "preventive protection" to ensure long-term ecological health. The remaining 7.55% of the territory consists of urban centers and water bodies, which were excluded from the prioritization modeling.

Table 3
Conservation priority assessment results

Area	**Conservation Priority**	**Area (km^2)**	**Area (hec)**	**Area (%)**
Stable Areas	Stable Low Priority	1118.95	111894.75	11.73
	Stable Medium Priority	2948.47	294846.75	30.90
	Stable High Priority	2292.65	229264.75	24.03
	Total Stable Areas	**6360.07**	**636006.3**	**66.66**
Unstable Areas	Unstable Low Priority	117.37	11737.00	1.23
	Unstable Medium Priority	427.43	42743.25	4.48
	Unstable High Priority	1916.04	191603.50	20.08
	Total Unstable Areas	**2460.84**	**246083.8**	**25.79**
Urban Area		338.50	33849.75	3.55
Water		381.15	38115.00	4.00
Total surface area		9540.55	954054.75	100.00

3.3 LULC Change and Spatio-Temporal Evolution (1985–2024)

Over the 40-year period from 1985 to 2024, the northeastern region of Rio de Janeiro underwent significant land use and land cover (LULC) transformations, marked by both pronounced gains and losses across multiple categories. The most substantial expansion occurred in Other Temporary Crops, which increased by 70.6% (+ 510.32 km²), followed by Pasture (+ 11.0%, + 408.33 km²) and Urban Area, which more than doubled (+ 115.8%, + 198.98 km²). Wetlands also expanded by 28.4% (+ 161.42 km²), while River, Lake and Ocean areas grew by 11.7% (+ 46.91 km²), as shown in Fig. 4.

Notably, several land cover types emerged or expanded from negligible baselines (Table 4), including Sugar Cane (+ 15.0 km²), Aquaculture (+ 0.57 km²), Forest Plantation (+ 0.30 km²), and Mining (+ 0.64 km², + 988.9%). Mangrove coverage increased by 67.8% (+ 3.49 km²), and Wooded Sandbank Vegetation rose by 23.0% (+ 15.28 km²). In contrast, the region experienced considerable declines in Mosaic of Uses, which decreased by 54.5% (− 1279.32 km²), and Beach, Dune and Sand Spot, which fell by 33.2% (− 74.08 km²). Herbaceous Sandbank Vegetation declined by 5.3% (− 26.30 km²), and Rocky Outcrop disappeared entirely (− 0.10 km², − 100%). Minor losses were also recorded in Savanna Formation (− 22.5%), Hypersaline Tidal Flat (− 17.6%), and Grassland (− 3.4%). These shifts reflect a landscape increasingly dominated by agricultural and urban expansion, coupled with the decline of mixed-use and natural coastal systems, highlighting ongoing anthropogenic pressures in this dynamic region of Brazil.

Table 4
LULC Change and Evolution (1985–2024)

TYPE	1985 (km^2)	1995 (km^2)	2005 (km^2)	2015 (km^2)	2024 (km^2)	Net Change (km^2)	Net Change (%)
Other Temporary Crops	723.17	1464.01	1391.17	1442.29	1233.49	510.32	70.6
Pasture	3697.13	4049.62	3969.42	4202.71	4105.47	408.33	11.0
Urban Area	171.83	253.38	305.86	350.41	370.82	198.98	115.8
Wetland	569.14	541.52	723.7	702.28	730.56	161.42	28.4
River, Lake and Ocean	400.52	412.67	394.95	352.83	447.43	46.91	11.7
Wooded Sandbank Vegetation	66.47	61.94	68.54	73.85	81.75	15.28	23.0
Sugar cane	0.0	0.39	9.45	1.01	15.0	15.0	100.0
Forest Formation	1554.39	1480.14	1490.91	1515.0	1566.96	12.57	0.8
Other non Vegetated Areas	36.58	10.03	42.66	27.04	43.55	6.97	19.1
Mangrove	5.15	6.21	7.34	8.83	8.64	3.49	67.8
Mining	0.06	0.13	0.22	0.6	0.71	0.64	988.9
Aquaculture	0.0	0.0	0.04	0.55	0.57	0.57	100.0
Forest Plantation	0.0	0.0	0.0	0.21	0.3	0.3	100.0
Savanna Formation	0.04	0.03	0.03	0.03	0.03	-0.01	-22.5
Hypersaline Tidal Flat	0.43	0.51	0.6	0.2	0.35	-0.08	-17.6
Rocky Outcrop	0.1	0.0	0.0	0.0	0.0	-0.1	-100.0
Grassland	27.01	26.64	26.81	27.72	26.09	-0.92	-3.4
Herbaceous Sandbank Vegetation	493.61	479.2	542.92	493.33	467.31	-26.3	-5.3
Beach, Dune and Sand Spot	222.98	227.74	122.71	171.6	148.9	-74.08	-33.2

TYPE	1985 (km^2)	1995 (km^2)	2005 (km^2)	2015 (km^2)	2024 (km^2)	Net Change (km^2)	Net Change (%)
Mosaic of Uses	2345.52	1299.95	1216.8	943.63	1066.2	-1279.32	-54.5
Total Area	10314.13						

4. Discussion

4.1 Interpreting Spatial Patterns of Degradation and Stability

The predominance of stable land (66.66%) in the study area, particularly along the coastal plains and the Paraíba do Sul River valley, highlights the stabilizing role of flatter topography and managed agricultural systems. These findings align with the general principle that low-gradient landscapes are less susceptible to high-energy surface runoff (Tahouri et al. 2022). The "green belt" effect provided by Managed Forest areas (10.54%) and Restinga vegetation (8.46%) is critical; these root systems anchor the soil and maintain its structure, acting as a primary defense against water-induced erosion (Henriques et al. 1986). However, the identification of 25.77% of the territory as unstable reveals a significant environmental vulnerability driven by the intersection of topography and historical land use.

The concentration of rill erosion in the Northwest Fluminense (16.31% of the total area) is largely an "eco-historical" legacy. Historically, this region underwent intense deforestation to accommodate cattle ranching and coffee cultivation, replacing dense Atlantic Forest with shallow-rooted pastures (Soffiati 2011). On the undulating slopes and interior plateaus, the removal of this protective canopy has left the soil directly exposed to meteoric impact, facilitating the development of rills as water concentrates in preferred pathways during heavy rainfall events (UNCCD, 2022). Our findings where rill erosion is most prevalent, align with the "return of erosive processes" observed in other Brazilian watersheds. As noted by Telles et al. (2019), even in regions that adopt advanced systems like No-Tillage, there is a growing tendency for farmers to abandon complementary mechanical practices such as agricultural terracing and contour farming.

Furthermore, the vulnerability of the Restinga and coastal sandbanks to sheet erosion in the Lakes Region underscores the "fragility" of these ecosystems when their protective vegetation is removed. As emphasized by Henriques et al. (1986), these specialized plant communities act as a primary stabilizer against wind and water action. The loss of these natural barriers, coupled with the lack of integrated soil and water conservation at the watershed scale, places the region at a high risk of long-term productivity decline and ecological impairment. By identifying these specific degradation "hotspots" and linking them to broader national management failures, this study provides a clear target for curative interventions in the interior and preventive protection along the coast.

4.2 Prioritization for Action: Curative and Preventive Strategies

The classification of 44.11% of the study area as High Priority (Priority I) underscores a critical state of environmental urgency in the northeastern Fluminense region. This high percentage suggests that nearly half of the landscape requires immediate institutional attention, though the nature of the required intervention varies. For the Unstable High Priority zones (20.08%), which are concentrated in the interior hilly regions like Itaperuna, the focus must be on curative measures. As highlighted by Tahouri et al. (2022), once rill erosion becomes generalized on steep slopes, natural recovery is unlikely without active soil stabilization, such as the implementation of terraces, check dams, and targeted reforestation with deep-rooted native species to restore soil cohesion. Conversely, the presence of 24.03% Stable High Priority land represents a "conservation treasure" that is under immediate threat. These are often the remaining fragments of the Atlantic Forest and dense restinga. According to Soffiati (2011), the historical expansion of the agricultural frontier in Rio de Janeiro has left these fragments isolated; their "High Priority" status implies that any further land-use change could trigger a rapid transition to an unstable state. Therefore, management in these zones should prioritize legal protection and the creation of ecological corridors to prevent the "tipping point" observed in the Northwest plateaus.

The identification of High Priority zones in the interior plateaus suggests that traditional environmental laws may not be enough; instead, Ecological-Economic Zoning (EEZ) should be implemented to regulate land use and encourage restoration. As demonstrated by Carvalho Costa et al. (2024) in other areas of the Atlantic Forest, EEZ instruments can be highly effective in containing anthropogenic threats and facilitating 'forest transition'—where regeneration rates begin to exceed deforestation.

The Medium Priority (35.38%) areas in the transitional margins and the Lakes Region represent the most cost-effective opportunity for land management. Because these areas are primarily suffering from sheet erosion rather than deep rilling, the degradation is still reversible through "soft" engineering and nature-based solutions. Protecting the restinga vegetation in Quissamã and Carapebus is paramount; as Henriques et al. (1986) established, this vegetation is the primary biological filter for coastal groundwater and the main stabilizer of the sandy substrate. If these "Medium Priority" zones are neglected, they will likely escalate into High Priority unstable lands within a few years due to the increasing frequency of extreme rainfall events associated with regional climate change (UNCCD 2022).

Finally, the Low Priority (12.96%) zones along the Paraíba do Sul alluvial plains should not be ignored. Their stability is a product of favorable topography, but their long-term health depends on maintaining sustainable agricultural practices. As suggested by UNEP/PAP (2000), the integration of GIS-based monitoring into municipal planning is essential to ensure that urban expansion (currently 3.55% of the area) does not spill over into these highly productive stable soils.

4.3 Temporal Landscape Evolution: Gains, Losses, and Vulnerabilities

The LULC transitions observed between 1985 and 2024 reveal a landscape undergoing intense homogenization and intensification. The most striking trend is the massive reduction in the Mosaic of Uses (− 54.5%, − 1279.32 km²), replaced primarily by Other Temporary Crops (+ 70.6%) and Pasture (+ 11.0%). This shift mirrors a "pervasive transition" of the broader Brazilian land-use system toward large-scale monoculture and livestock grazing. According to Strassburg et al. (2014), this expansion of agricultural frontiers is often unnecessary, as the current productivity of Brazilian cultivated pasturelands is only 32–34% of its potential. Increasing this efficiency to approximately 50% could meet future production demands without further conversion of the fragile Atlantic Forest fragments identified in this study. Furthermore, Soffiati (2011) notes that this intensification in the North and Northwest Fluminense is a primary driver of rill erosion, as pasture expansion on undulating terrains frequently occurs without adequate soil conservation practices.

The 115.8% expansion of Urban Areas (+ 198.98 km²) is another critical finding, particularly along the coastal strip. This rapid urbanization correlates with the 33.2% loss of Beaches, Dunes, and Sand Spots and the 5.3% decline in Herbaceous Sandbank Vegetation (Restinga). These systems are experiencing "coastal squeeze" (UNCCD 2022), trapped between rising sea levels and advancing infrastructure. The loss of these barriers is concerning as the Restinga serves as the "final line of defense" against the sheet erosion documented in the Lakes Region (Henriques et al., 1986).

Interestingly, the region shows signs of ecological resilience in certain niches, such as the 67.8% increase in Mangroves and the 23.0% rise in Wooded Sandbank Vegetation. These gains align with observations in other coastal protected areas of Rio de Janeiro, where mangroves have shown relative stability despite high levels of surrounding anthropization (Santos et al. 2022). While these gains reflect the success of local environmental protection laws, they remain small in absolute area compared to the loss of Herbaceous Restinga (− 26.30 km²) and Grasslands.

The virtual disappearance of Rocky Outcrops (− 100%) and the decline in Hypersaline Tidal Flats (− 17.6%) suggest that even specialized micro-habitats are being altered by human activities like mining (+ 988.9%). Collectively, these dynamics illustrate that while some "green" categories are recovering, the overall trend is toward a landscape more vulnerable to degradation, where stabilizing natural cover is being traded for short-term economic agricultural and urban utility (MapBiomas 2025; Tahouri et al. 2022; Santos et al. 2022; Strassburg et al. 2014).

4.4 Methodological Constraints and Future Research Directions

While the PAP/RAC methodology and MapBiomas data provide a robust framework for assessing land degradation, several limitations must be acknowledged.

- Data Resolution and Edge Effects: The use of 30-meter resolution Landsat imagery is highly effective for regional assessments but may under-represent small-scale degradation features. For example, incipient rill erosion or narrow corridors of riparian vegetation restoration may fall below

the detection threshold of a 30m pixel. Furthermore, the 30-meter resolution introduces a well-known 'edge effect' along complex coastlines. As detailed in our methodology (Section 2.3), we corrected for this by normalizing all area calculations to the official municipal vector boundaries (9,543.27 km²) to ensure consistency. Future research could integrate high-resolution Sentinel-2 (10m) or UAV (drone) imagery for "hotspot" areas like the Northwest Fluminense to capture finer soil loss dynamics.

- Temporal Frequency and Seasonality: This study utilized ten-year intervals to capture long-term trends. However, land cover in tropical regions can fluctuate rapidly due to seasonal cycles or extreme weather events (e.g., flash floods). The MapBiomas annual datasets provide a significant advantage here, but the specific "target years" chosen might reflect specific climatic anomalies (exceptionally dry or wet years) that influence the appearance of vegetation health and soil moisture in the satellite signal.
- Implications for Policy and Planning: Despite these limitations, the results provide a clear roadmap for municipal and state environmental planning. The identification of "Priority I" zones in the interior plateaus suggests that traditional command-and-control environmental laws may not be enough; instead, Payment for Environmental Services (PES) programs should be directed toward landowners in Itaperuna and Miracema to encourage the transition from degraded pasture to silvopastoral systems.

In coastal zones, the "Medium Priority" status of the Lakes Region implies that urban master plans (Planos Diretores) must enforce stricter setbacks from the coastline. Protecting the remaining "Wooded Sandbank Vegetation" is not just a biodiversity concern but a physical necessity to prevent further sheet erosion and coastal instability. By integrating these GIS-based priority maps into public policy, authorities can move from reactive disaster management to proactive landscape restoration (UNEP/PAP 2000; Tahouri et al. 2022).

5. Conclusion

This study successfully applied a multi-temporal geospatial approach, adapting the PAP/RAC framework, to assess land degradation and conservation priorities in the northeastern region of Rio de Janeiro State. By integrating high-resolution satellite imagery with decades of land-use data, several critical conclusions can be drawn regarding the environmental health of this dynamic landscape. First, while 66.66% of the territory is currently classified as stable, this stability is geographically concentrated in the low-lying coastal plains and alluvial valleys. The remaining 25.77% of the land is actively undergoing degradation, with rill erosion identified as the primary threat, particularly in the hilly interior of the Northwest Fluminense. These "hotspots" of instability are the direct result of historical forest suppression and the continued expansion of cattle ranching on steep, vulnerable slopes. Second, the conservation priority assessment reveals that nearly half of the study area (44.11%) requires urgent intervention. This includes 20.08% of the landscape that needs immediate curative restoration to halt active erosion and 24.03% of stable land that requires strict preventive protection to maintain its existing

ecological services. The identification of these zones provides a scientific basis for local authorities to transition from reactive disaster management to proactive land-use planning. Third, the 39-year spatio-temporal analysis (1985–2024) illustrates a landscape undergoing rapid transformation, characterized by the doubling of urban areas and a significant decline in traditional mosaic land uses. The resulting "coastal squeeze" and fragmentation of fragile ecosystems, such as the restinga, have increased the vulnerability of coastal zones to sheet erosion and soil thinning.

In summary, the northeastern quadrant of Rio de Janeiro faces a critical environmental "tipping point". The results of this study underscore that sustainable regional development will only be achieved by integrating rigorous geospatial monitoring into public policy. This integrated geospatial approach offers a replicable model for assessing land degradation vulnerability in other tropical coastal regions facing similar pressures. Future management must prioritize the restoration of degraded interior pastures and the legal protection of coastal vegetation fragments to ensure the long-term resilience of these vital ecosystems in the face of both anthropogenic pressure and climatic shifts

Declarations

Competing interests:

”The authors have no relevent financial or non-financial to disclose”.

Ethics approval:

Not Applicable

Consent to Participate

Declaration: Not Applicable

Consent to Publish

Declaration: Not Applicable

Ethical Statement

All authors have read, understood, and have complied as applicable with the statement on ‘Ethical responsibilities of Authors’ as found in the Instructions for Authors.

Clinical trial number

not applicable.

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Author Contribution

“All authors have contributed to the study conception design and material preparation, data collection and analysis. The first draft of the manuscript was written by author 1 and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.”

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Data Availability

The MapBiomas land use and land cover data that support the findings of this study are publicly available at https://mapbiomas.org. The very-high-resolution Airbus imagery (2025) and Esri World Imagery used in this study were accessed under licence and are not publicly available. Restrictions apply to the availability of these licensed data. Data from this study are however available from the corresponding author upon reasonable request and with permission of the respective data providers (Airbus and Esri).

Code availability:

Not applicable

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Figures

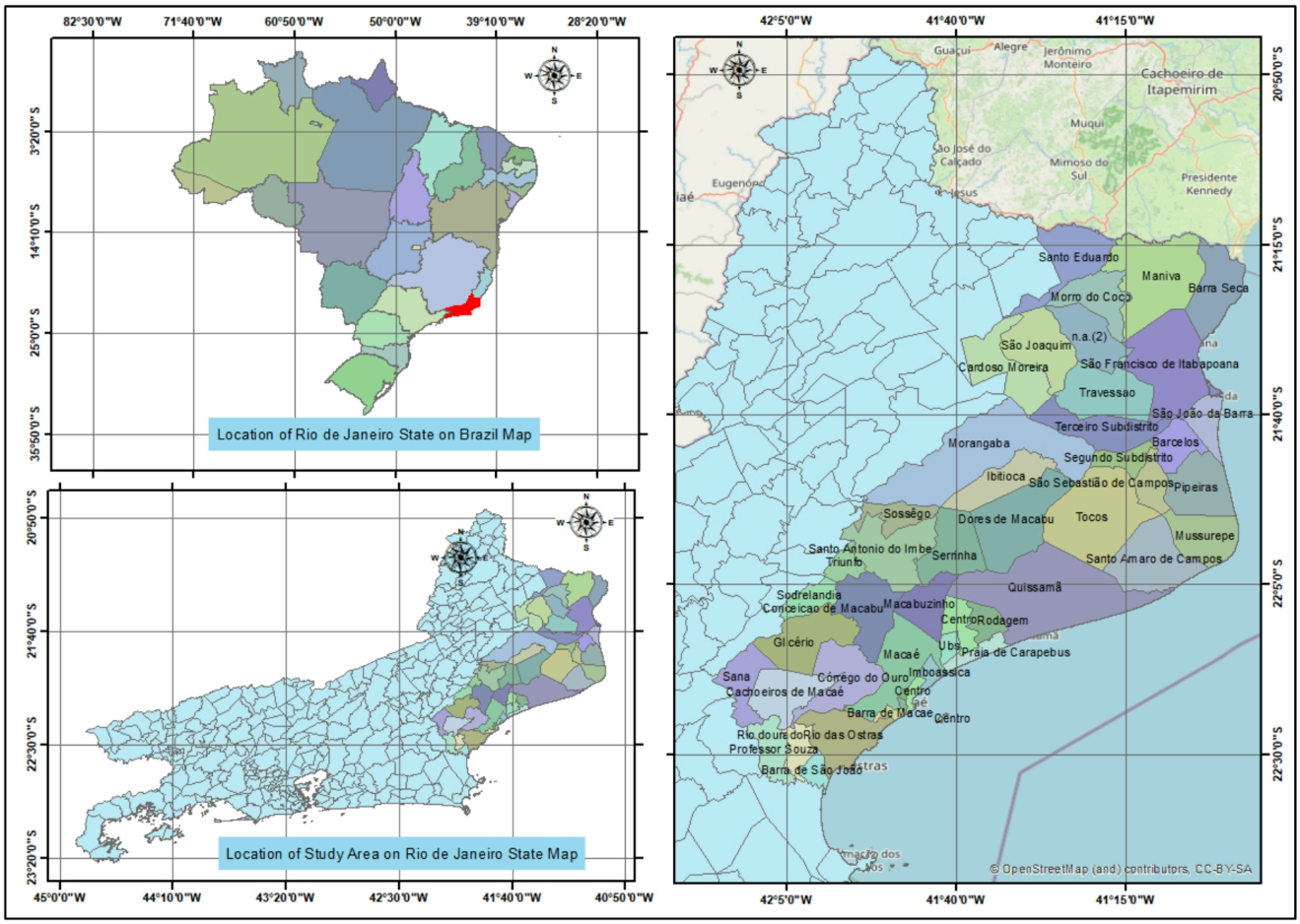


Figure 1

Location map of the study area in the northeastern region of Rio de Janeiro State

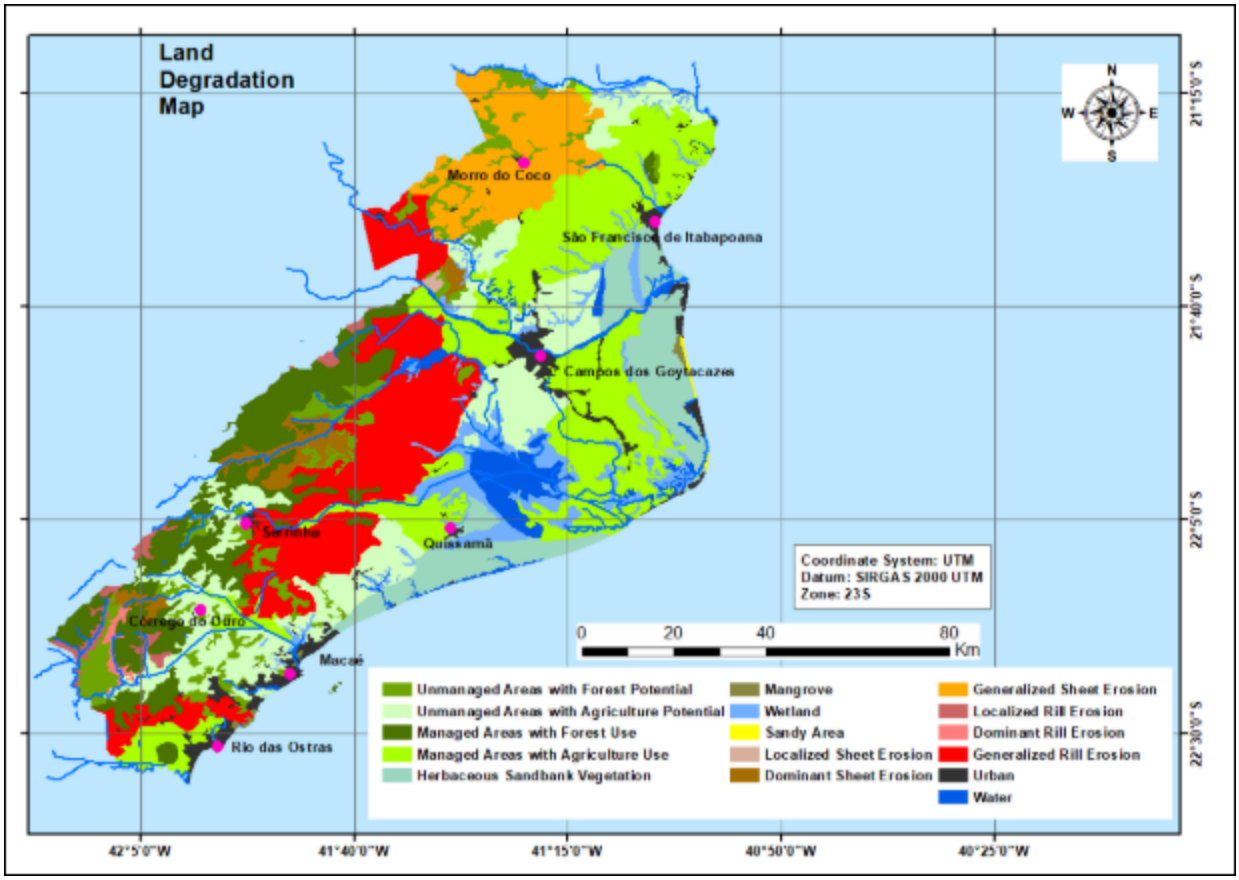


Figure 2

Spatial distribution of land degradation stability and instability classes derived from the PAP/RAC analysis (2025 baseline)

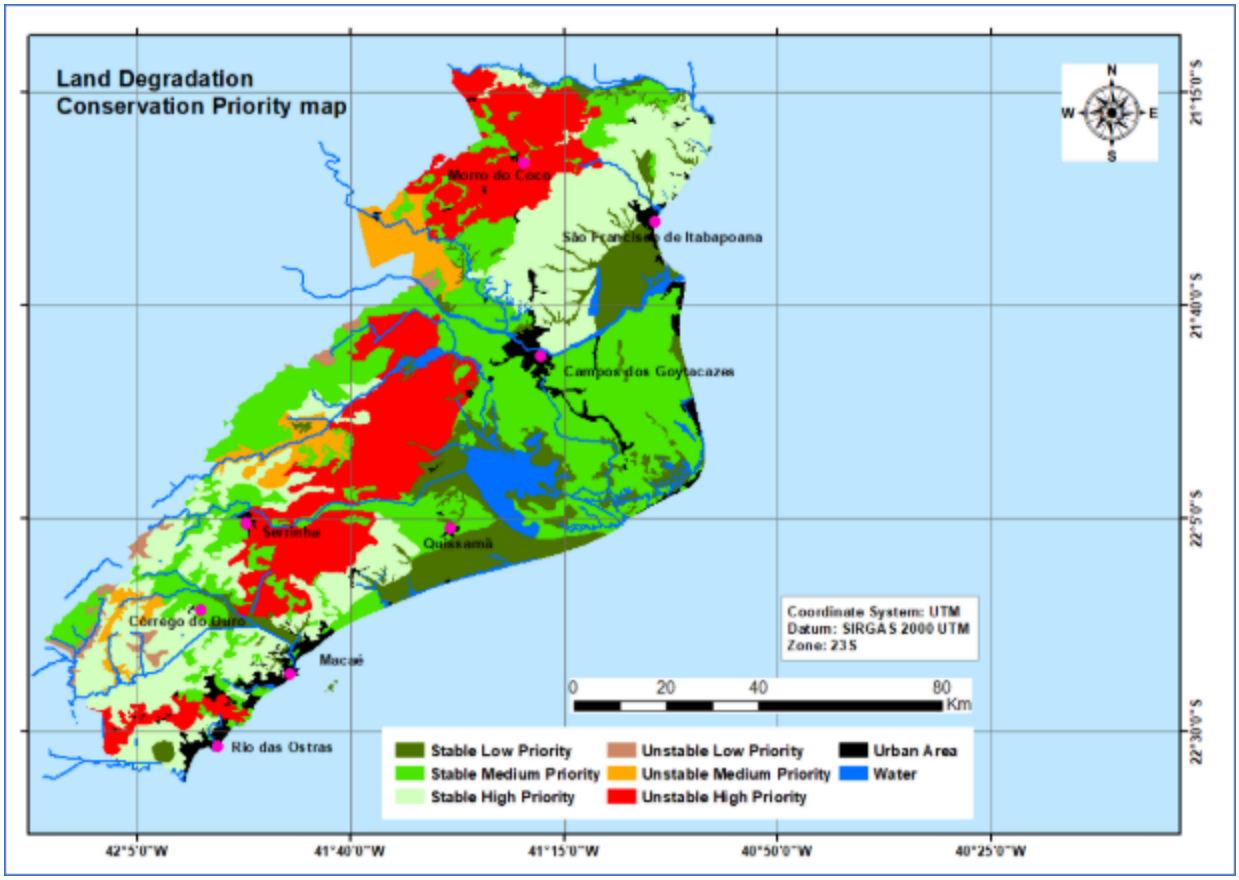


Figure 3

Conservation priority map classifying areas into Low, Medium, and High priority for intervention

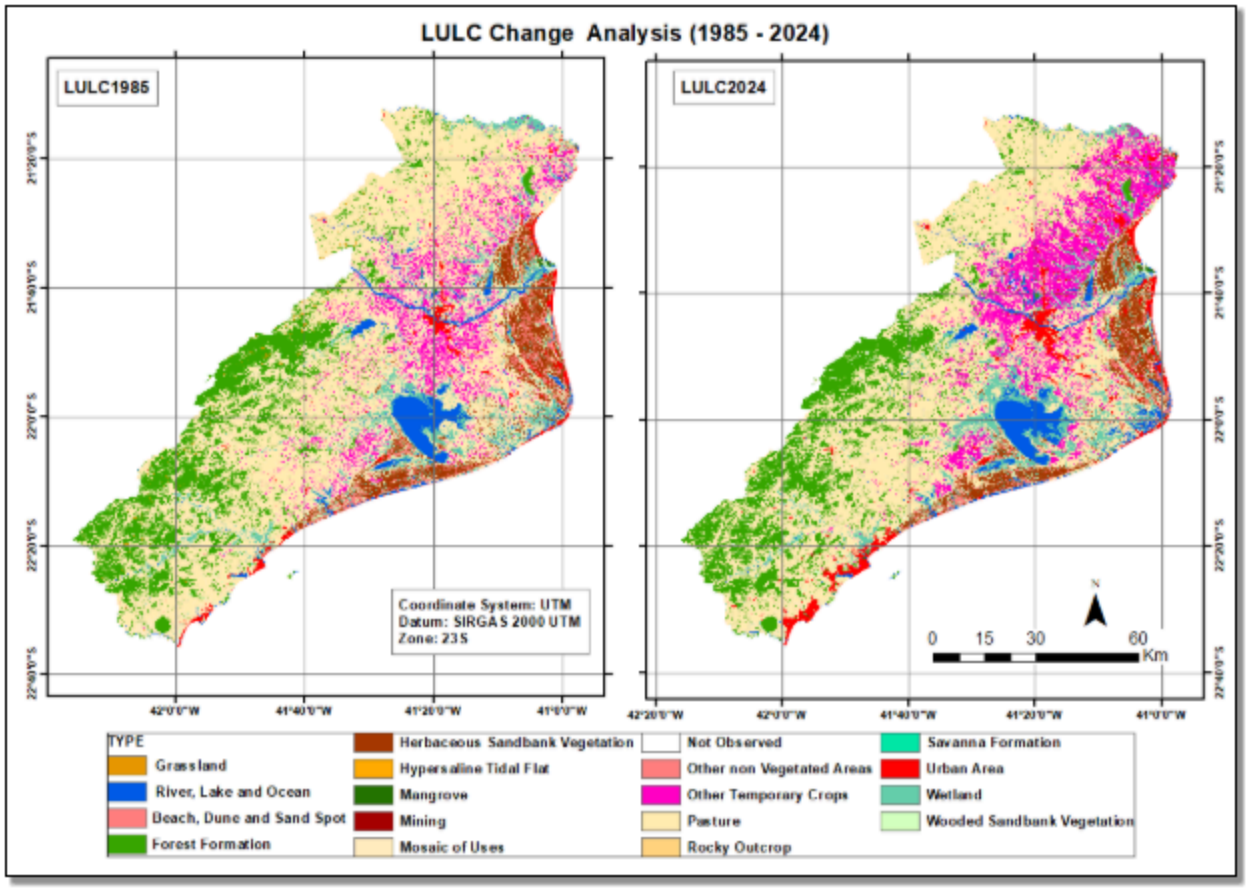


Figure 4

Landuse/Landcover Changes between 1985 and 2024