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From past transitions to future landscape trajectories: land use dynamics in two tropical Brazilian river basins

Rafael Alvarenga ALMEIDA *[1], Thiago Ferreira de ARAÚJO [1], Daniel Brasil Ferreira PINTO [1], Glaucio Ferreira LOUREIRO [1], Camila de Sousa Queiroz ALMEIDA [1]

[1] Federal University of the Jequitinhonha and Mucuri Valleys, Teófilo Otoni, MG, Brazil.
*E-mail: rafael.almeida@ufvjm.edu.br

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ABSTRACT: This study addresses the spatiotemporal evolution of land use and land cover (LULC) in the Mucuri and Jequitinhonha river basins, eastern Brazil, aiming to provide a detailed analysis for researchers, planners, and policymakers in data-scarce regions. Using MapBiomas data at 30 m spatial resolution and scenario modeling through MOLUSCE, the study aimed to: (i) quantify LULC transitions between 1985 and 2021; (ii) analyze spatial patterns of anthropogenic expansion and vegetation dynamics; and (iii) simulate future scenarios for 2033 and 2045. The results indicate that approximately 30% of the area of both basins underwent significant changes. In the Mucuri Basin, forest recovery was observed in headwater areas, possibly associated with conservation policies, whereas the Jequitinhonha Basin showed apparent forest stability, masking the expansion of eucalyptus monocultures and agricultural areas. The simulations indicate continued pressure on native vegetation, with projected forest loss exceeding 5% in the Mucuri Basin. Model validation, with Kappa values between 0.68 and 0.72, indicates reliable projections. The study highlights the importance of integrated modeling for environmental planning and management.
Keywords: MapBiomas; MOLUSCE; spatiotemporal evolution.

Das transições passadas às trajetórias de paisagens futuras: dinâmica do uso da terra em duas bacias hidrográficas tropicais brasileiras

RESUMO: Este estudo aborda a evolução espaço-temporal do uso e da cobertura da terra (LULC) nas bacias dos rios Mucuri e Jequitinhonha, no leste do Brasil, com o objetivo de fornecer uma análise detalhada para pesquisadores, planejadores e formuladores de políticas públicas em áreas com escassez de dados. Utilizando o MapBiomas, com resolução de 30 m, e a modelagem de cenários com o MOLUSCE, o estudo visa (i) quantificar as transições de LULC entre 1985 e 2021, (ii) analisar os padrões espaciais de expansão antrópica e a dinâmica da vegetação, e (iii) simular cenários para 2033 e 2045. Os resultados indicam que cerca de 30% das áreas de ambas as bacias sofreram mudanças significativas. Na bacia do Mucuri, observou-se recuperação florestal nas cabeceiras, possivelmente associada a políticas de conservação, enquanto a bacia do Jequitinhonha apresentou uma aparente estabilidade florestal, mascarando expansões de monoculturas de eucalipto e áreas agrícolas. As simulações indicam pressão contínua sobre a vegetação nativa, com perda florestal superior a 5% projetada para o Mucuri. A validação do modelo, com Kappa entre 0,68 e 0,72, indica que as projeções são confiáveis. O estudo destaca a importância da modelagem integrada para o planejamento e gestão ambiental.
Palavras-chave: MapBiomas; MOLUSCE; evolução espaço-temporal.

1. INTRODUCTION

Land use and land cover (LULC) changes are among the most significant anthropogenic drivers of environmental transformation worldwide. In recent decades, pressures related to population growth, agricultural expansion, urbanization, and global commodity markets have intensified the conversion of natural landscapes, particularly in tropical and subtropical regions (MEYFROIDT et al., 2022). These transformations often result in habitat loss, land degradation, changes in the hydrological cycle, and carbon fluxes, threatening both biodiversity and ecosystem services (SONG et al., 2018; TEIXEIRA et al., 2023).

Monitoring and modeling spatiotemporal patterns of LULC are thus essential for guiding environmental planning and developing sustainable land management strategies. Remote sensing techniques, when integrated with Geographic Information Systems (GIS), have enabled unprecedented capabilities for assessing land change dynamics across spatial and temporal scales (LU; WENG, 2007; SOUZA JUNIOR et al., 2020). In Brazil, the MapBiomas project represents a milestone in environmental monitoring, providing consistent annual LULC data from 1985 onwards based on Landsat imagery, and has become a key tool for research and policy-making (SOUZA JUNIOR et al., 2020).

Beyond historical assessments, predictive modeling of land cover is increasingly used to forecast possible future scenarios and support decision-making under uncertainty. Among the various available tools, the MOLUSCE (Modules for Land Use Change Simulation) plugin in QGIS stands out

by combining cellular automata and artificial neural networks to simulate landscape changes based on past trends and environmental variables (FETENE et al., 2023; LUKAS et al., 2023). These models allow researchers to assess potential trajectories of land use expansion, deforestation, and environmental risk under different assumptions.

The Mucuri and Jequitinhonha River Basins, located in the northeastern region of Minas Gerais State and southern Bahia State, Brazil, represent socially and ecologically critical landscapes. Despite their strategic importance, both basins face increasing pressure from agriculture, cattle ranching, forest plantations, and urban growth, leading to the degradation of native vegetation and hydrological alterations (MAGALHÃES JÚNIOR et al., 2019; ALMEIDA et al., 2020; PEREIRA et al., 2022; TEIXEIRA et al., 2023). Moreover, policy interventions, such as the creation of the Alto Mucuri Environmental Protection Area in 2011, have attempted to mitigate such impacts, yet their effectiveness remains underexplored.

In this context, this study aims to analyze land use and land cover changes in the Mucuri and Jequitinhonha River Basins from 1985 to 2021 and simulate future scenarios for 2033 and 2045 using remote sensing data and spatial modeling techniques. Specifically, we (i) quantified historical LULC transitions using MapBiomas data integrated into GIS tools, (ii) assessed the spatial patterns of anthropogenic expansion and forest dynamics, and (iii) applied the MOLUSCE plugin to simulate possible future landscapes.

2. MATERIALS AND METHODS

2.1. Study Area

The Mucuri and Jequitinhonha River Basins are located in eastern Brazil (Figure 1), encompassing regions in the northeastern Minas Gerais State and the southern Bahia State. Together, these basins cover an area of approximately 85,000 km² and are subject to diverse climatic, topographic and pedological conditions that influence land use and hydrological processes (CODEVASF, 2021b).

Geomorphologically, the region features heterogeneous relief, ranging from the rugged highlands of the Espinhaço Mountain Range in the upper Jequitinhonha to the coastal plains of the lower Mucuri. Soils are predominantly deeply weathered Latosols (Oxisols) and Argisols (Ultisols) in flatter and undulating terrains, with shallower Cambisols and Neosols occurring in the steeper and semi-arid portions of the Jequitinhonha basin. In terms of vegetation, the study area spans three major Brazilian biomes: the Atlantic Forest, which originally dominated the Mucuri basin and the lower Jequitinhonha; the Cerrado (Brazilian savanna) in the upper and middle Jequitinhonha; and the Caatinga (semi-arid biome) in the middle-lower Jequitinhonha (CODEVASF, 2021a, 2021b). To ensure accurate spatial analysis and area calculations, all geospatial datasets were projected to the SIRGAS 2000 Albers Equal Area Conic coordinate reference system.

The Mucuri River Basin (BHRM) comprises 23 municipalities (21 in Minas Gerais State and 2 in Bahia State), spanning a drainage area of approximately 15,400 km² with a population of 535,267 inhabitants. The climate in this basin is predominantly classified as tropical with dry winters (Aw), according to the Köppen-Geiger system. However, a transition to a humid tropical climate (Af) occurs in areas adjacent to the Espírito Santo state, where the dry season is shorter (Beck et al., 2023).

According CODEVASF (2021a) the Jequitinhonha River Basin (BHRJ) is significantly larger, with a drainage area of approximately 69,500 km² and an estimated population of 1,445,405. It extends across 92 municipalities, including 13 in Bahia State and 79 in Minas Gerais State. The region experiences climatic diversity, primarily within the Aw (tropical with dry winters) and BSh (hot semi-arid) classifications. Annual precipitation varies widely, from 600 mm in semi-arid zones to 1,600 mm in more humid areas, concentrated between October and March (FERREIRA; SILVA, 2012; BECK et al., 2023).

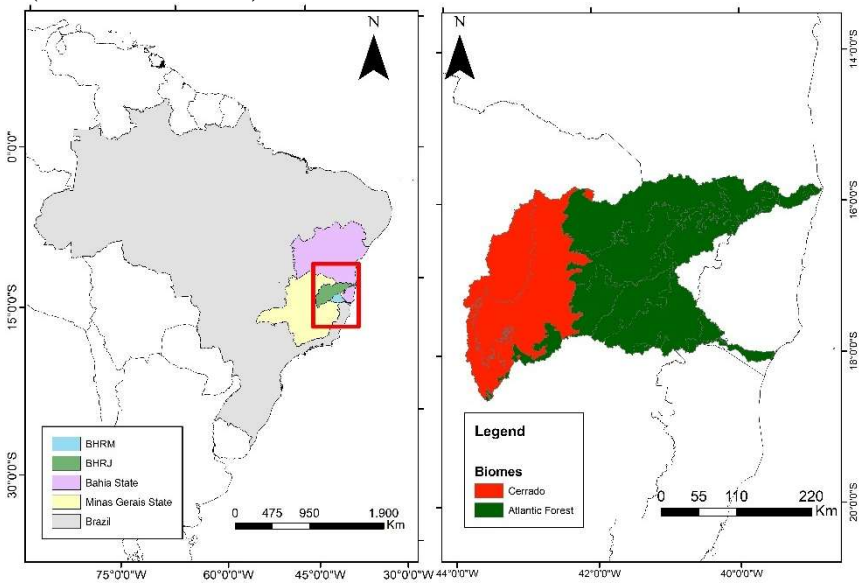


Figura 1. Mapa de localização e respectivos biomas das bacias hidrográficas dos rios Mucuri e Jequitinhonha. Fonte: MapBiomas (2022) and IBGE (2024).

Figure 1. Location and biome maps of the Mucuri and Jequitinhonha River Basins. Data sources: MapBiomas (2022) and IBGE (2024).

2.2. Data sources and classification scheme

To analyze historical LULC dynamics, we utilized the MapBiomas Collection 7.1, which provides annual LULC maps for Brazil derived from the Landsat satellite archive (Landsat 5 TM, 7 ETM+, and 8 OLI) with a 30-meter spatial resolution (SOUZA JUNIOR et al., 2020). Potential

inconsistencies, such as missing data due to cloud cover or sensor anomalies, are mitigated by MapBiomas through pixel-level temporal filters and gap-filling algorithms applied within the Google Earth Engine platform, ensuring consistent annual time series (SOUZA JUNIOR et al., 2020).

Four key time points (1985, 1997, 2009, and 2021) were selected for the change detection analysis. The year 1985 represents the baseline of the MapBiomas historical series. The subsequent 12-year intervals were strategically chosen to capture long-term decadal trends and political-economic cycles of land occupation. This temporal spacing filters out short-term interannual fluctuations and allows sufficient time for significant landscape transitions, such as agricultural consolidation and secondary forest succession, to become spatially established and detectable.

The MapBiomas classification legend was simplified into six aggregated classes based on hydrological and ecological relevance: 1. Forest; 2. Grassland; 3. Pasture; 4. Agriculture; 5. Non-Vegetated Area; and 6. Water. All data were processed using QGIS 3.30.2, and raster reclassification was performed to group original MapBiomas categories into the six classes listed above.

2.3. GIS-based processing workflow

To ensure full reproducibility of the geospatial analysis, a workflow was structured into sequential processing stages, moving from data acquisition to scenario simulation (Figure 2).

The spatial analyses were conducted in QGIS 3.30.2, integrating specific plugins to perform landscape metrics, land use change detection, and predictive modeling. Each stage is described as follows:

A. Landscape Statistics with LecoS: We used the Landscape Ecology Statistics (LecoS) plugin (Jung, 2016) to calculate the total area and percentage of each LULC class. These metrics were generated for both basins across the years 1985, 1997, 2009, and 2021, enabling a clear temporal comparison.

B. Change Detection with SCP Plugin: Temporal changes were quantified using the Semi-Automatic Classification Plugin (SCP) (CONGEDO, 2021). We applied a cross-classification algorithm to perform pixel-by-pixel comparisons across the designated time intervals (1985–1997, 1985–2009, and 1985–2021). This operation generated spatially explicit transition matrices, allowing the precise identification of which land-cover classes persisted and which were converted.

C. Data Structuring for Scenario Modeling: The output matrices and reclassified maps then served as the foundational input for the predictive modeling phase.

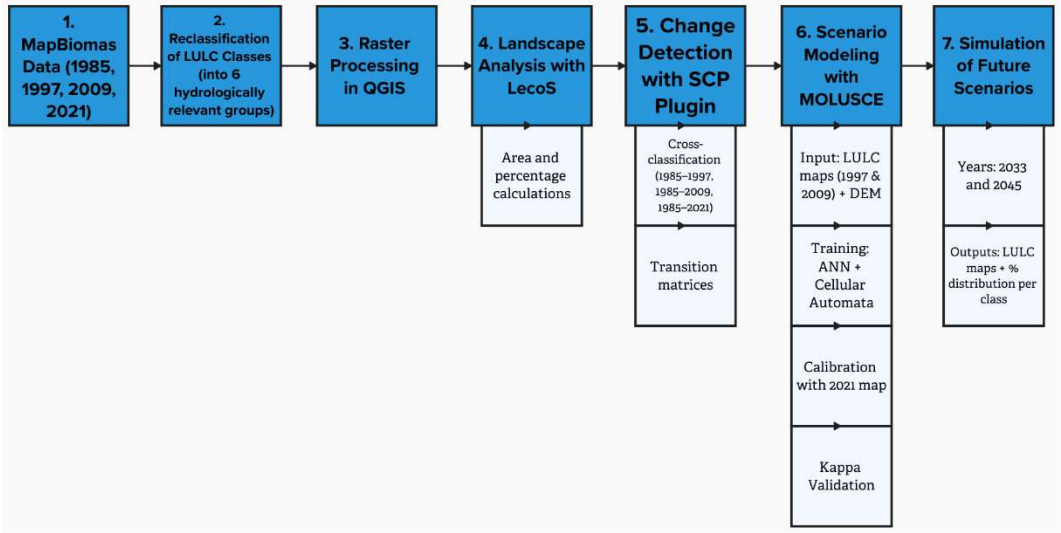


Figura 2. Fluxograma ilustrativo do fluxo metodológico para análise do uso e cobertura do solo e simulação de cenários utilizando o QGIS, MapBiomas e MOLUSCE.

Figure 2. Flowchart illustrating the methodological workflow for LULC analysis and scenario simulation using QGIS, MapBiomas, and MOLUSCE.

2.4. Land use change modeling and scenario simulation

To simulate future LULC scenarios for 2033 and 2045, we employed the MOLUSCE (Modules for Land Use Change Evaluation) plugin, which couples Artificial Neural Networks (ANN) with Cellular Automata (CA) to model landscape transitions based on historical spatial dynamics (FETENE et al., 2023; LUKAS et al., 2023).

A. Model Calibration and Input Data: The simulation utilized the reclassified maps of 1997 and 2009 as base years. For environmental predictors, elevation and slope were selected because regional topography is a primary determinant constraining agricultural mechanization, urban expansion, and forest preservation in these basins. These topographic variables were derived from a Digital Elevation Model (DEM) acquired from the Shuttle Radar Topography Mission (SRTM) via Topodata - INPE. The ANN was calibrated using a 3 × 3-pixel neighborhood window to capture spatial dependencies, extracting 10,000 automatic training samples, and running over 100 iterations to minimize classification errors.

B. Model Validation: The transition probability matrix calculated between 1997 and 2009 was used to simulate the 2021 LULC map, which was then compared against the actual 2021 MapBiomas data. The predictive performance yielded Kappa coefficients of 0.68 for BHRM and 0.72 for BHRJ. The model performance was considered acceptable for scenario projection (KAMARAJ; RANGARAJAN, 2022). Therefore, according to Landis; Koch (1977), these

values indicate substantial agreement, confirming that the model's spatial allocations are reliable for projecting macroscopic, business-as-usual land-use trajectories. However, it is important to acknowledge the limitations of this validation framework. Pixel-based metrics like Kappa can conservatively penalize minor spatial shifts (near-misses) even if the overall landscape dynamics are accurately captured (PONTIUS; MILLONES, 2011). Furthermore, the validation assumes historical stationarity, meaning the model accurately reflects past pressures but inherently cannot forecast abrupt socio-environmental disruptions, such as sudden policy shifts or severe climate shocks.

C. Scenario Generation (2033 and 2045): After validation, the calibrated model was used to simulate LULC maps for:

- 2033: A short-to-medium-term projection;
- 2045: A long-term projection aligned with national and global policy cycles (e.g., Agenda 2030, climate goals).

These scenarios reflect business-as-usual trends, assuming that current land use patterns, environmental drivers, and policy conditions persist. Although MOLUSCE does not incorporate dynamic socioeconomic variables, the model provides valuable insights into the spatial expansion or contraction of key LULC classes under historical transformation trajectories.

3. RESULTS

3.1. Overall historical LULC change in the Mucuri and Jequitinhonha River Basins

The analysis of LULC in the Mucuri (BHRM) and Jequitinhonha (BHRJ) River Basins between 1985 and 2021 revealed significant landscape transformations. The total area undergoing LULC change during the study period reached 31.97% in BHRM and 29.95% in BHRJ, reflecting a high degree of spatial reorganization.

Demographic dynamics were also considered to support the interpretation of the spatial reconfiguration observed in both basins. According to IBGE data (1997; 2024), BHRM experienced a moderate population increase of 12.6% between 1991 and 2020, while BHRJ grew more intensely, with a 52.4% increase. This growth was accompanied by accelerated urbanization: the proportion of urban population in BHRM rose from 56% to 70%, and in BHRJ from 47% to 66% between 1991 and 2010.

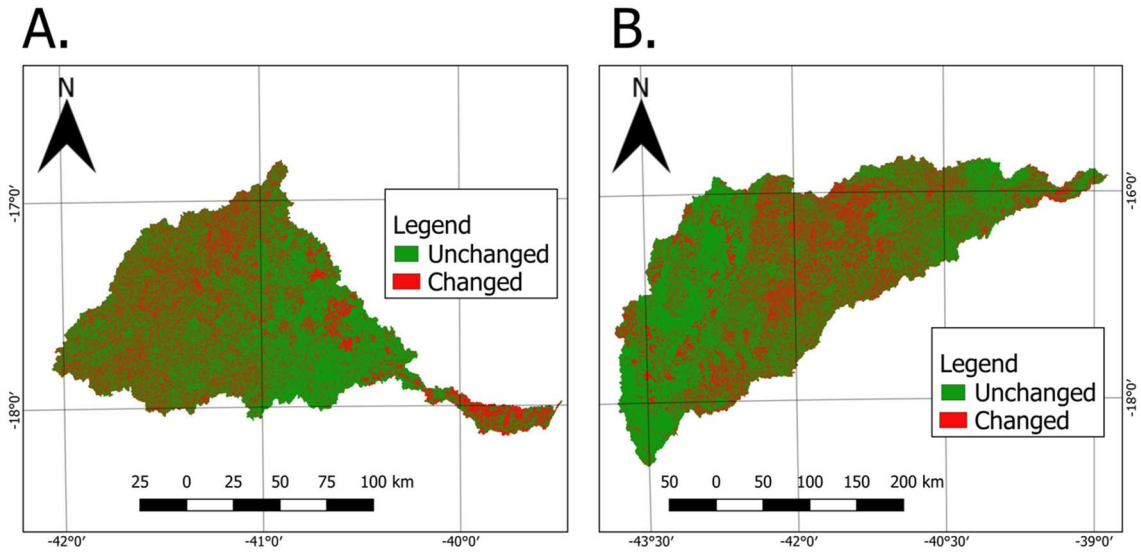


Figure 3. Land use change map from 1985 to 2021: (A) BHRM and (B) BHRJ.
Figura 3. Alterações no uso e na ocupação do solo entre 1985 e 2021: (A) BHRM e (B) BHRJ.

Tabela 1. Comparação entre as populações urbanas e rurais de 1991 a 2010 (em %).
Table 1. Comparison of Urban and Rural Population between 1991 and 2010 (in %).

	1991		2010	
Region	Urban	Rural	Urban	Rural
BHRM	56	44	70	30
BHRJ	47	53	66	34

Source: IBGE (2024).
Fonte: IBGE (2024).

3.2. Historical LULC dynamics in the BHRM

The series of LULC maps for 1985, 1997, 2009, and 2021 demonstrates that the central portion of the Mucuri River Basin experienced a marked decline in pasture areas, while the headwater region showed consistent increases in forest cover. Forest cover in BHRM increased from 29.8% in 2009 to nearly 34% in 2021. At the same time, the pasture class, which represented 55.63% of the basin in 1985, dropped to 47.81% by 2021.

The grassland class, although still dominant in absolute terms, with 6,304.5 km² in 2021, showed a reduction of 1,284 km² since 1997. The detailed land use transition data presented in Table 2 provide strong evidence of dynamic landscape flux. The transition from grassland to agriculture reached 580.1 km², while the transition from forest to agriculture reached 989.6 km² between 1985 and 2021. Conversely, the reversion from agriculture to forest reached 589.6 km², and grassland to forest reached 387.0 km² over the same period.

3.3. Historical LULC dynamics in the BHRJ

The analysis of land use and land cover (LULC) in the BHRJ from 1985 to 2021 revealed a complex mosaic of transformations. Spatially explicit LULC maps show that the central portion of the basin underwent the most intense land cover changes, predominantly associated with the replacement of native vegetation by pastures, croplands, and silviculture.

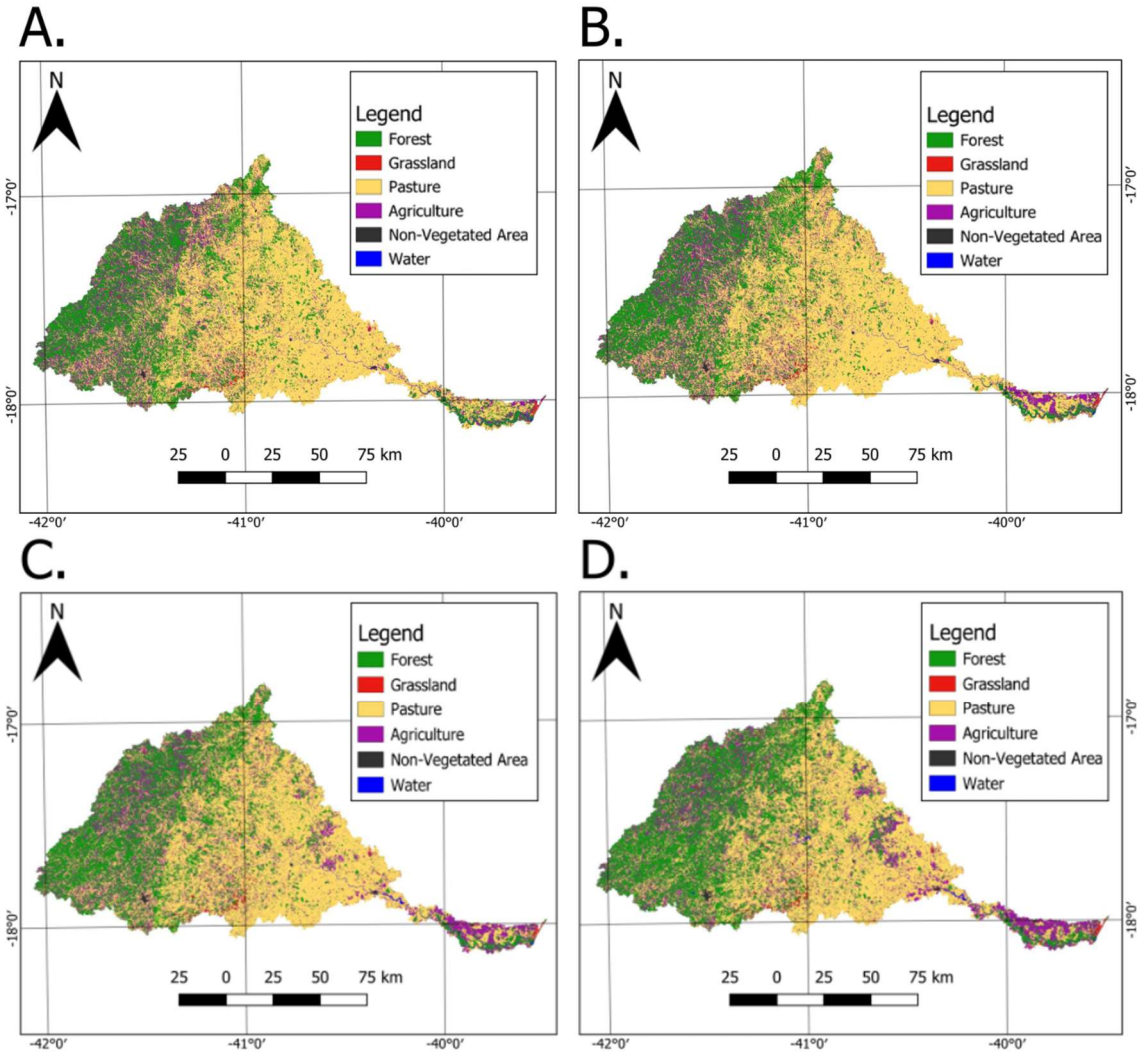


Figure 4. Land Use and Land Cover Maps of the BHRM for the years: (A) 1985; (B) 1997; (C) 2009; and (D) 2021.
Figura 4. Mapas de uso e ocupação do solo na BHRM para os anos: (A) 1985; (B) 1997; (C) 2009; e (D) 2021.

Between 1985 and 2021, the forest class remained the dominant LULC category, but with a net decrease from 54.71% to 54.06%, indicating relative stability in percentage terms. However, Table 3 shows that more than 2,400 km² of forested areas were converted into agriculture, pasture, and grassland, reflecting substantial losses in absolute terms. The grassland class, while relatively stable in percentage, underwent significant internal dynamics. Over 3,198 km² originally classified as grassland were converted into forests, and another 2,798 km² into agriculture. Conversely, more than 2,400 km² of forest was converted into grasslands.

The pasture class declined only modestly in absolute area, from 2,873.6 km² in 1985 to 2,847.8 km² in 2021. However, continuous transformations were observed: nearly 100 km² were converted into agriculture, while over 90 km² came from forest. Agricultural land increased from 14.77% to 17.01% over the study period, reflecting a trend of expansion. The conversion from forest and grassland to agriculture in the BHRJ occurred mainly in the central basin. Table 3 presents the land use data from 1985 to 2021 for the BHRJ. The comparisons are divided into three time periods: between 1985 and 1997, between 1985 and 2009, and between 1985 and 2021.

The modest changes in non-vegetated areas and water bodies are also worth noting. Despite their small share, the non-vegetated class grew from 0.11% to 0.21%. Water bodies also increased from 0.20% to 0.26%.

3.4. Model validation

The MOLUSCE model showed satisfactory performance, with Kappa values of 0.68 for BHRM and 0.72 for BHRJ, indicating substantial agreement between observed and simulated maps (Landis & Koch, 1977). These values are consistent with acceptable standards in LULC simulation literature (Pontius & Millones, 2011; Fetene et al., 2023).

3.5. Future LULC scenarios for 2033 and 2045

Using the MOLUSCE plugin and historical land use transitions between 1997 and 2009, future LULC scenarios were simulated for the years 2033 and 2045 under a business-as-usual (BAU) framework. These projections assume the continuation of existing land-use dynamics, excluding policy shifts, climate events, or market shocks. The results reveal distinct transformation patterns between the Mucuri and Jequitinhonha Basins.

3.5.1. BHRM

The LULC maps generated for the BHRM indicate an ongoing intensification of land conversion, particularly in the headwater and central regions of the basin.

The most pronounced projected change is a decrease in forest cover, from 33.28% in 2033 to 28.06% in 2045, representing a net loss of over 5%. Simultaneously, agriculture expands from 10.15% to 16.90%, reflecting a continuation of land conversion trends historically observed in the region.

The pasture class, while still dominant, is projected to decline modestly from 55.71% to 54.09%, suggesting that pastureland is being partially replaced by agriculture. While small in absolute terms, the projected increase in water bodies from 0.24% to 0.30% and the stabilization of non-vegetated areas were also observed in the simulated scenarios.

3.5.2. BHRJ

Simulated LULC maps for the BHRJ display a different dynamic. The central portion of the basin, already affected by extensive land-use pressure, continues to be the focal point for transformations.

The most significant trend is a gradual reduction in forest cover, from 55.88% in 2033 to 53.20% in 2045, primarily due to conversion to pasture and, to a lesser extent, non-vegetated areas.

Agriculture in the BHRJ is projected to decline slightly, from 17.40% to 15.75%. The increase in pasture from 22.10% to 25.82% indicates expansion of this class in the future scenarios. Non-vegetated areas, although still a minor component, are projected to increase from 0.11% to 0.46%. Similarly, water bodies should increase from 0.20% to 0.43%.

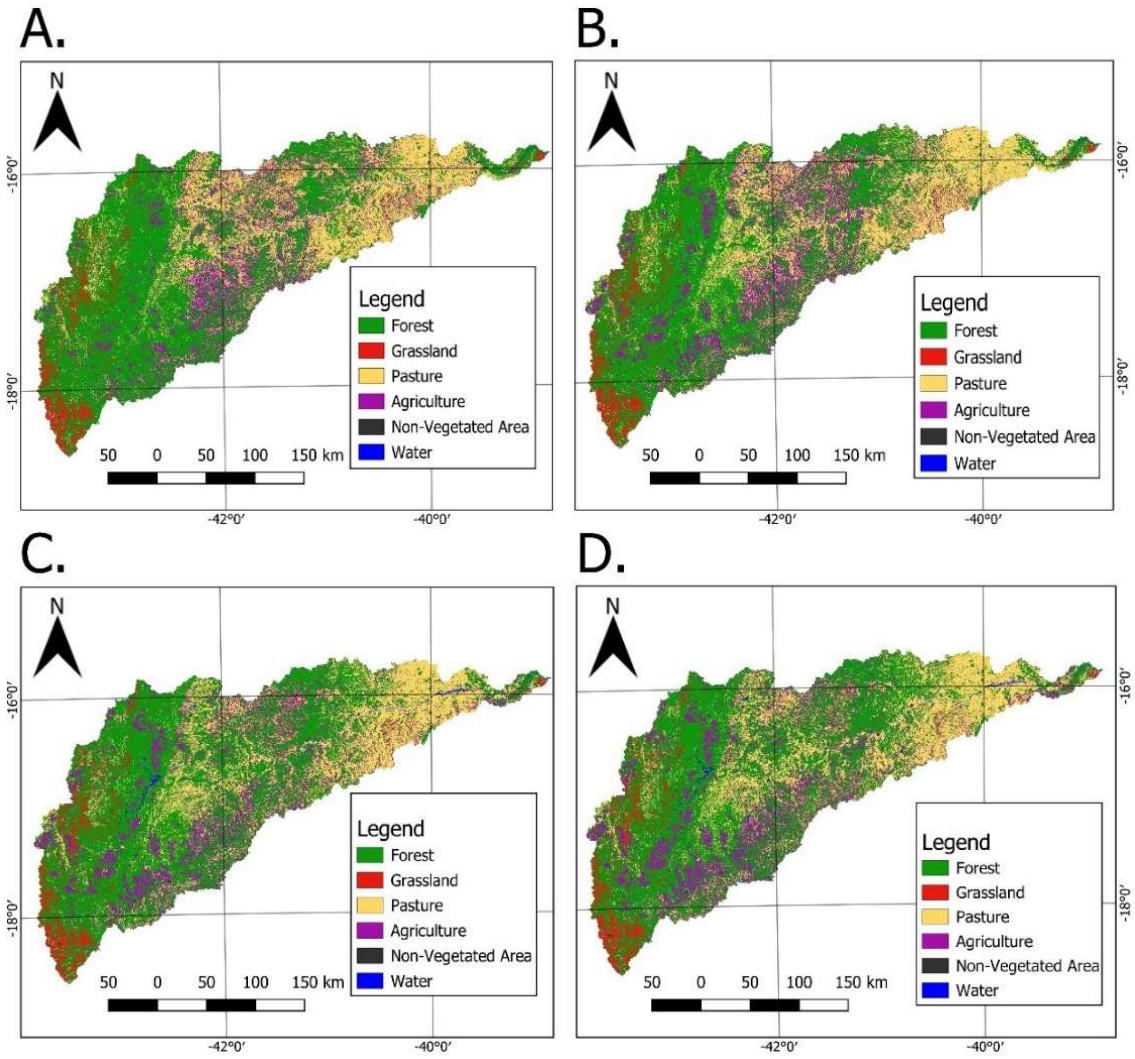


Figure 5. Land Use and Land Cover Maps of the BHRJ for the years: (A) 1985; (B) 1997; (C) 2009; and (D) 2021.
Figura 5. Mapas de uso e ocupação do solo na BHRJ ao longo dos anos: (A) 1985; (B) 1997; (C) 2009; e (D) 2021.

4. DISCUSSION

4.1. Historical land-use reorganization and anthropogenic pressure

The observed rates of LULC change in the Mucuri and Jequitinhonha River Basins are consistent with national trends observed in the Brazilian Atlantic Forest and semi-arid transition zones, where agricultural frontiers, urbanization, and silviculture have intensified in recent decades (SONG et al., 2018; TEIXEIRA et al., 2023). Similar rates of landscape transformation were also documented by Souza Junior et al. (2020), who found that land conversion exceeded 25% of total area in most Brazilian biomes over a 35-year span.

Such demographic shifts align with findings from Macedo et al. (2020), who emphasized that demographic

pressure and rural-to-urban migration often lead to land abandonment in marginal areas and intensified use near urban centers, driving deforestation, forest fragmentation, and land degradation. Bueno et al. (2009), analyzing deforestation patterns in BHRM, also identified a negative correlation between forest cover and proximity to urban centers and roads, reinforcing the idea that accessibility remains a key driver of land conversion in the region.

Tabela 2. Mudança no uso do solo em comparação ao uso original na BHRM.
Table 2. Land Use Change Compared to Original Land Use in the BHRM.

Original Land Use	New Land Use	1985-1997 (Km²)	1985-2009 (Km²)	1985-2021 (Km²)
Forest	**Forest (inaltered)**	**3415.3**	**3248.5**	**3261.5**
	Pasture	2.4	2.9	3.2
	Grassland	299.6	400.7	913.9
	Agriculture	526.9	591.1	989.6
	Non-Vegetated Area	0.4	0.9	0.4
	Water	2.4	3.0	14.7
Pasture	Forest	2.9	2.8	3.8
	Pasture (inaltered)	**67.0**	**73.3**	**77.6**
	Grassland	14.7	13.0	18.0
	Agriculture	21.7	16.9	26.7
	Non-Vegetated Area	0.4	0.6	0.5
	Water	0.2	0.2	1.0
Grassland	Forest	247.0	511.9	387.0
	Pasture	7.4	10.4	8.3
	Grassland (inaltered)	**7588.6**	**6957.2**	**6304.5**
	Agriculture	725.4	1077.0	580.1
	Non-Vegetated Area	8.3	14.9	7.1
	Water	3.9	9.3	5.5
Agriculture	Forest	624.2	777.8	589.6
	Pasture	10.4	15.6	16.5
	Grassland	554.0	639.7	1308.5
	Agriculture (inaltered)	**1260.3**	**1012.2**	**844.8**
	Non-Vegetated Area	4.3	6.6	3.6
	Water	2.9	4.3	12.7
Non-Vegetated Area	Forest	0.0	0.5	1.7
	Pasture	0.4	0.4	1.0
	Grassland	9.7	8.5	22.5
	Agriculture	1.4	2.1	9.7
	Non-Vegetated Area (inaltered)	**19.9**	**20.0**	**20.0**
	Water	0.2	0.2	0.6
Water	Forest	4.9	6.9	3.6
	Pasture	0.2	0.4	0.1
	Grassland	7.3	5.1	13.4
	Agriculture	4.6	9.2	5.3
	Non-Vegetated Area	0.3	0.3	0.1
	Water (inaltered)	**39.4**	**34.8**	**22.0**

4.2. Conservation effects and land-use transitions in the BHRM

The spatial pattern observed in the Mucuri River Basin coincides with the establishment of the Alto Mucuri Environmental Protection Area (EPA) in 2011, which encompasses approximately 325,000 hectares (PEREIRA, 2018). The increase in forest cover from 29.8% in 2009 to nearly 34% in 2021 supports the interpretation that conservation policies may have had tangible effects in the region. The effectiveness of protected areas in promoting forest recovery has also been confirmed in other studies, such as Pereira (2018), who demonstrated that Brazilian APAs can mitigate land conversion even in regions of high land-use conflict.

The decline in pasture areas reflects both conversion to agriculture and secondary succession, possibly driven by changing land-use profitability and policy enforcement. Similar conversions have been observed in the Paraíba Valley, Southeast Brazil, where degraded pastures were either transformed into eucalyptus plantations or gradually reverted to shrub vegetation (PEREIRA et al., 2022).

Tabela 3. Mudança no uso do solo em comparação ao uso original na BHRJ.
Table 3. Land Use Change Compared to Original Land Use in the BHRJ.

Original Land Use	New Land Use	1985-1997 (Km²)	1985-2009 (Km²)	1985-2021 (Km²)
Forest	**Forest (inaltered)**	**32832.2**	**31849.5**	**30406.6**
	Pasture	20.1	33.1	37.8
	Grassland	1631.8	2101.6	2427.2
	Agriculture	3537.7	3947.8	5058.3
	Non-Vegetated Area	21.6	33.3	54.3
	Water	14.0	92.2	73.2
Pasture	Forest	26.7	22.4	23.6
	Pasture (inaltered)	**2873.6**	**2924.2**	**2847.8**
	Grassland	162.3	109.1	166.2
	Agriculture	75.7	82.2	92.3
	Non-Vegetated Area	11.6	13.7	23.7
	Water	6.6	4.9	2.9
Grassland	Forest	1180.8	2827.3	3198.2
	Pasture	99.0	172.4	152.7
	Grassland (inaltered)	**14117.8**	**11928.3**	**11609.7**
	Agriculture	2455.4	2864.8	2798.7
	Non-Vegetated Area	26.8	42.1	81.6
	Water	27.1	72.1	66.0
Agriculture	Forest	2410.0	3769.9	3925.4
	Pasture	39.8	80.7	88.6
	Grassland	2118.0	2226.7	2353.2
	Agriculture (inaltered)	**5680.4**	**4148.8**	**3834.9**
	Non-Vegetated Area	11.8	19.0	41.1
	Water	13.6	28.5	30.4
Non-Vegetated Area	Forest	6.4	8.4	10.3
	Pasture	8.2	9.4	8.6
	Grassland	29.8	29.2	32.6
	Agriculture	23.8	27.3	27.5
	Non-Vegetated Area (inaltered)	**98.4**	**89.7**	**87.3**
	Water	5.8	8.5	6.2
Water	Forest	23.8	36.8	45.8
	Pasture	4.9	19.4	38.0
	Grassland	19.1	20.8	40.1
	Agriculture	16.7	23.8	22.7
	Non-Vegetated Area	16.3	7.0	9.6
	Water (inaltered)	**266.3**	**239.5**	**190.9**

Part of the grassland transition can be attributed to the conversion of grasslands to croplands and forests, indicating a reorganization of low-productivity lands. Rather than drawing analogies with distant mountain ranges, this pattern is characteristic of regional land-use shifts in eastern Brazil, where the abandonment of marginal, low-fertility lands allows for the gradual expansion of secondary vegetation. Similar landscape reorganizations, driven by shifting agricultural viability and demographic changes, have been widely documented across the semi-arid transition zones of Minas Gerais, confirming that local socioeconomic dynamics

directly shape these ecosystem recovery trajectories (PEREIRA et al., 2022; ARAÚJO et al., 2023).

The reversion from agriculture to forest and from grassland to forest suggests ecological recovery processes potentially linked to land abandonment or conservation initiatives. Conversely, the transition from grassland to agriculture and from forest to agriculture indicates that frontier expansion remains active in parts of the basin.

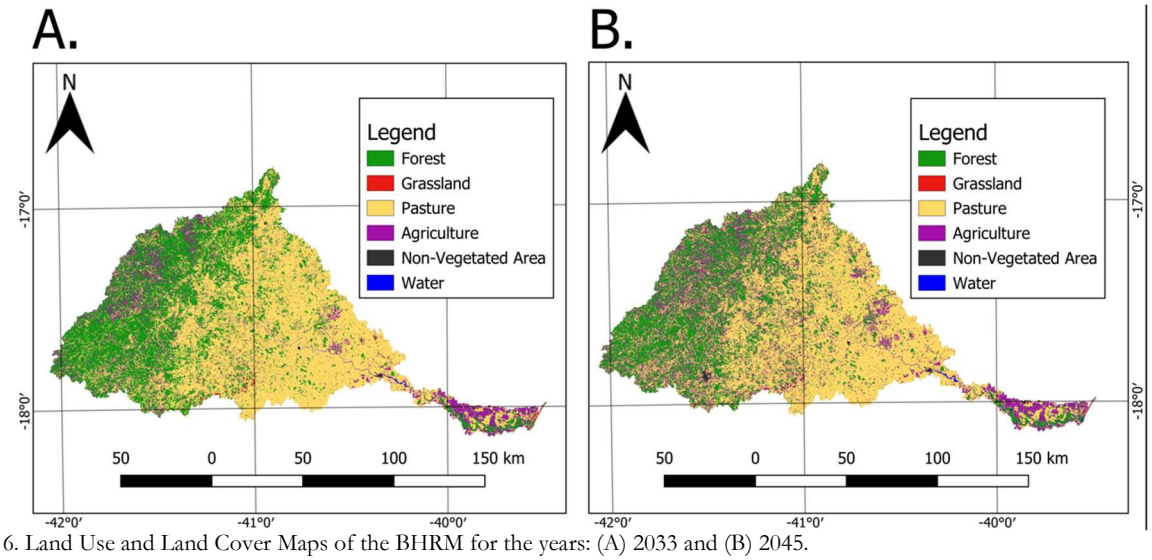


Figure 6. Land Use and Land Cover Maps of the BHRM for the years: (A) 2033 and (B) 2045.
Figura 6. Mapa de uso e ocupação do solo da BHRM ao longo dos anos: (A) 2033 e (B) 2045.

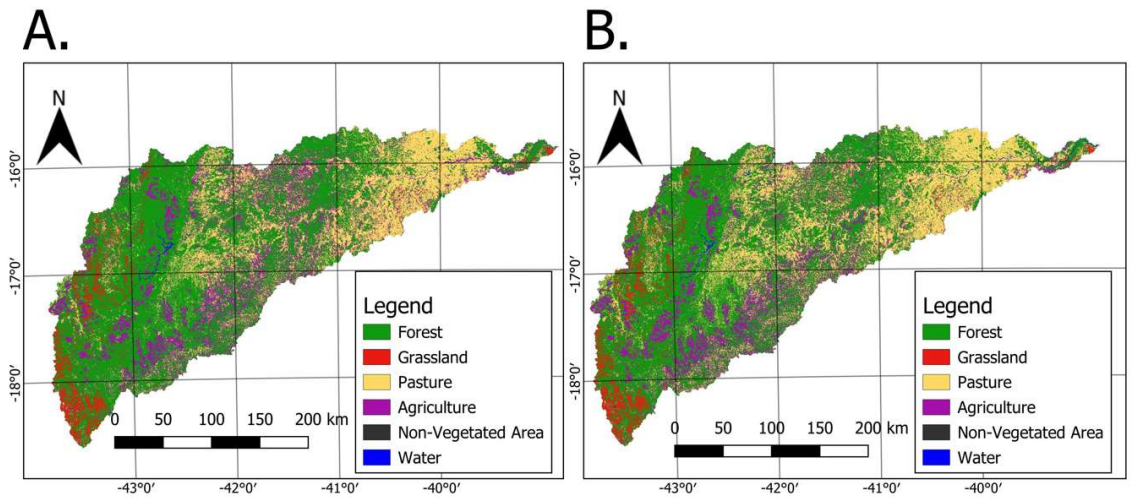


Figure 7. Land Use and Land Cover Maps of the BHRJ for the years: (A) 2033 and (B) 2045.
Figura 7. Mapa de uso e ocupação do solo da BHRJ para os anos: (A) 2033 e (B) 2045.

4.3. Apparent forest stability and hidden land-use transitions in the BHRJ

In the Jequitinhonha River Basin, the apparent stability of the forest class can be misleading. The classification adopted in this study followed the MapBiomas structure, in which eucalyptus plantations are included within the "Forest" class. This methodological aspect is crucial to interpretation. As observed by Pereira et al. (2022), eucalyptus monoculture has rapidly expanded in the region since the 1970s, promoted by public incentives and large-scale land acquisitions. In areas such as Chapada das Veredas, native vegetation cover declined from 86.1% in 1973 to just 24.6% in 2018, with eucalyptus taking its place.

The bidirectional transitions between forest, grassland, agriculture, and pasture reinforce the idea of a highly dynamic landscape. These transitions may reflect rotational cycles, fallow periods, land degradation, or the replacement of native ecosystems by planted forests and agricultural systems. These bidirectional dynamics are best understood through the lens of regional socioenvironmental shifts. For instance, Araújo et al. (2023) highlighted how historical land-use changes and the continuous suppression of native vegetation in the Gravatá River micro-basin (Araçuaí-MG) have led to severe socioenvironmental impacts, including soil degradation and reduced water availability. Similarly, human-driven interventions to support regional water and agricultural demands, such as the Setúbal River dam in Jenipapo de Minas, further illustrate how intensely the landscape is reorganized, altering both ecological balances and local livelihoods (MAGALHÃES JÚNIOR et al., 2019; GONÇALVES, 2024).

Agricultural expansion in the BHRJ also aligns with studies such as Teixeira et al. (2023), who linked agricultural intensification to global commodity markets and internal migration within the Brazilian Southeast. Thus, the conversion from forest and grassland to agriculture occurred at the expense of ecological integrity, especially in the central basin.

The modest increase in non-vegetated areas may indicate localized urbanization or soil degradation. The increase in water bodies may reflect either changes in the hydrological regime or improved classification over time. Together, these dynamics reveal intensifying competition for land, with eucalyptus plantations, mechanized agriculture, and extensive pastures competing for space formerly occupied by native ecosystems. The expansion of eucalyptus, in particular, raises severe ecological concerns regarding biodiversity and ecosystem services.

The substitution of heterogeneous native vegetation with homogeneous monocultures eliminates structural habitat complexity, driving local biodiversity loss. Furthermore, this hidden transition compromises critical ecosystem services. Hydrologically, fast-growing exotic plantations exhibit higher evapotranspiration rates than native biomes, which can reduce baseflows and exacerbate water scarcity in a basin already facing semi-arid climate pressures (PEREIRA et al., 2022). Additionally, intensive silvicultural practices contribute to soil nutrient depletion and alter belowground biological communities (JUAN-OVEJERO et al., 2025). Therefore, while remote sensing metrics suggest a stable 'forest' extent, the BHRJ is actually experiencing a qualitative degradation of its ecological integrity and functional resilience.

4.4. Future landscape trajectories and implications for watershed management

The projected scenarios for 2033 and 2045 indicate the continuation of historical land-use trends, although with distinct trajectories between the two basins. In the Mucuri River Basin, the projected decrease in forest cover and simultaneous expansion of agriculture suggest increasing pressure on native vegetation and conservation-sensitive areas.

This transition is particularly concerning, given that much of the projected deforestation is concentrated near ecologically sensitive areas. Although the Alto Mucuri Environmental Protection Area (EPA) remains legally protected and unchanged in extent, buffer zones and adjacent landscapes are projected to undergo significant degradation. This reinforces the need for landscape-scale conservation approaches, as isolated protected areas may be insufficient to prevent biodiversity loss or hydrological disruption (PEREIRA, 2018).

The projected decline in pasture and expansion of agriculture in BHRM align with recent studies indicating that livestock activities in southeastern Brazil are becoming spatially compressed and more intensive, with pasture giving way to row crops in flatter, more accessible terrains (TEIXEIRA et al., 2023).

In the Jequitinhonha River Basin, the projected gradual reduction in forest cover reflects persistent pressure from extensive cattle ranching and low-regulation land uses, particularly in regions where enforcement of conservation policy is limited (PEREIRA et al., 2022). The projected slight decline in agriculture may indicate the displacement of productive activity by extensive pastures, the abandonment of marginal croplands, or model feedback effects based on a recent deceleration in agricultural expansion. Rather than reflecting broad national trends, this land-use retraction is a well-documented regional phenomenon in the Jequitinhonha Valley, where historical cycles of occupation, severe soil degradation, and restricted water availability often force the abandonment of traditional croplands, which are subsequently converted into lower-yield pastures or eucalyptus plantations (MAGALHÃES JÚNIOR et al., 2019; PEREIRA et al., 2022; ARAÚJO et al., 2023).

The increase in pasture projected for the BHRJ may suggest the intensification of extensive livestock systems, particularly in areas previously covered by forests or secondary vegetation. This pattern is consistent with the regional land tenure dynamics of northeastern Minas Gerais, where extensive grazing remains a primary driver of deforestation and landscape homogenization, particularly under conditions of weak local land governance (PEREIRA et al., 2022).

The projected increase in non-vegetated areas may be associated with growing urban fringes, degraded lands, or misclassified open surfaces. Similarly, the increase in water bodies may reflect improved mapping in flat, flooded areas or model artifacts related to topographic flow.

4.5. Model performance, uncertainty, and methodological limitations

The Kappa values obtained for BHRM and BHRJ indicate substantial agreement between observed and simulated maps (LANDIS; KOCH, 1977). These values are consistent with acceptable standards in LULC simulation literature (Pontius; Millones, 2011; Fetene et al., 2023), supporting the use of the simulated scenarios as baseline projections.

However, while MOLUSCE provides spatially explicit and interpretable projections, the model fundamentally relies on historical stationarity and does not account for socioeconomic shocks, infrastructure investments, or sudden policy changes.

This is a critical limitation, as regional research has extensively demonstrated that territorial and socioenvironmental dynamics in the Jequitinhonha and Mucuri valleys are deeply governed by complex land tenure disputes, large-scale silviculture expansion, and local water management interventions that mathematical models struggle to capture (PEREIRA et al., 2022; ARAÚJO et al., 2023; GONÇALVES, 2024). Therefore, the scenarios should not be interpreted as deterministic forecasts, but rather as business-as-usual trajectories that must be analyzed alongside the region's rich socio-territorial literature.

To bridge the gap between pixel-based spatial modeling and regional socioenvironmental research, Table 4 summarizes key local studies that highlight the underlying drivers of land-use change and their qualitative impacts.

These studies demonstrate that future land-use trajectories in both basins will be strongly dictated by environmental regulation enforcement, commodity prices, and climate-related disturbances. Consequently, rather than treating these basins as environments lacking data, a perspective that overlooks decades of robust sociological and geographical research, future modeling efforts should strive to integrate these qualitative territorial variables. Despite current methodological limitations, the spatial patterns simulated here offer a baseline that, when coupled with regional socioenvironmental knowledge, can support proactive, socially aware watershed management.

Table 4. Summary of regional socioenvironmental studies and their main conclusions regarding territorial dynamics in the study area.
Tabela 4. Resumo dos estudos socioambientais regionais e suas principais conclusões sobre as dinâmicas territoriais na área de estudo.

Author(s) & Year	Study Focus Area	Main Conclusions on Socioenvironmental Dynamics
Magalhães Júnior et al. (2019)	Jequitinhonha River Basin	Demonstrated that aggressive LULC changes directly degrade surface water quality, altering the basin's hydrological resilience and affecting local populations.
Pereira et al. (2022)	Upper Jequitinhonha (Chapada)	Concluded that public-incentivized eucalyptus monoculture drives intense land and water concentration, drastically reducing native vegetation and impacting traditional community livelihoods.
Araújo et al. (2023)	Gravatá River (Araçuaí-MG)	Identified that historical land-use changes and native vegetation suppression have triggered severe soil degradation and structural water scarcity in the micro-basin.
Gonçalves (2024)	Setúbal River (Jenipapo de Minas)	Highlighted that anthropogenic infrastructure interventions, while aiming to solve water deficits, profoundly alter ecological balances and local socioenvironmental relations.

5. CONCLUSIONS

This study analyzed historical and projected land use and land cover (LULC) dynamics in the Mucuri and Jequitinhonha River Basins between 1985 and 2045. Rather than simply quantifying spatial area, the integration of long-term remote sensing and predictive modeling revealed critical, often hidden, landscape transformations.

Historically, the Mucuri River Basin exhibited partial forest recovery in headwater regions, likely influenced by conservation efforts, though simultaneous agricultural expansion remains active. In contrast, the Jequitinhonha River Basin demonstrated a misleading stability in its forest class, which actually conceals a profound ecological substitution of native vegetation by fast-growing eucalyptus monocultures and extensive pastures. Simulated scenarios for 2033 and 2045 indicate that under business-as-usual conditions, pressure on native ecosystems and water resources will intensify in both basins.

To mitigate these impacts, watershed management must evolve beyond the creation of isolated protected areas. We specifically recommend the implementation of stricter ecological-economic zoning, the establishment of ecological corridors to reconnect fragmented habitats, and rigorous regulation of large-scale silviculture to safeguard regional hydrological resilience.

Future research should address the limitations of purely spatial and stationary modeling by integrating dynamic socioeconomic variables, such as land tenure disputes, agricultural commodity market fluctuations, and demographic shifts. Furthermore, incorporating climate change projections and ecosystem service valuation into hybrid modeling frameworks will provide a much more robust and policy-relevant foundation for sustainable territorial planning in these complex tropical basins.

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