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Spatiotemporal dynamics of land use and land cover in the iron quadrangle and its protected areas from 1985 to 2020

Abstract

Land use and land cover changes pose significant challenges to biodiversity conservation, particularly in regions affected by intensive mining activities and the expansion of human land use. This study aimed to analyze the spatiotemporal dynamics of land use and land cover in the Iron Quadrangle, Minas Gerais, Brazil, and its Protected Areas (PAs) from 1985 to 2020. Annual land use and land cover data from MapBiomas Collection 6, derived from Landsat imagery at a spatial resolution of 30 m, were used. Geoprocessing techniques within a Geographic Information System (GIS) environment were applied to perform spatial clipping, reprojection, and area calculations, enabling the quantification of changes in land use and land cover classes. The analysis included Protected Areas classified under the Strict Protection and Sustainable Use groups, excluding their buffer zones. The results revealed substantial land use and land cover transformations across the Iron Quadrangle, with increases of 278% in forestry plantations, 273% in mining areas, and 53% in urbanized areas. Additionally, savanna formations increased by 40%, whereas forest formations declined by approximately 5%. Within Protected Areas, changes were observed in land cover classes associated with human activities, alongside the expansion of certain natural vegetation formations. These findings highlight the coexistence of land transformation processes and the persistence or expansion of specific vegetation classes, emphasizing the importance of systematic monitoring of protected landscapes. The study concludes that geospatial multitemporal analysis provides a valuable tool for supporting land management, environmental planning, and biodiversity conservation strategies in mining-intensive regions.

Keywords: remote sensing, geoprocessing, iron quadrangle, land use and land cover change, protected areas, mining, biodiversity conservation

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Abbreviations: GIS, geographic information system; PA, protected area; Pas, protected areas

Introduction

Land use and land cover (LULC) changes are among the main drivers of natural landscape transformation, influencing biodiversity, water resources, ecosystem services, and environmental dynamics. In Brazil, the expansion of agricultural, mining, forestry, and urban activities has intensified anthropogenic pressures on ecosystems, particularly in regions characterized by high biological diversity and economic importance. The expansion of agricultural activities and commodity production in the Brazilian Cerrado has contributed to significant changes in land use patterns, raising concerns about native vegetation conversion and the environmental consequences of agricultural frontier expansion.[1] In this context, the spatiotemporal analysis of LULC changes provides a valuable approach to understanding territorial transformation processes and supporting environmental planning and conservation strategies.

Among the Brazilian regions experiencing intensive land transformations, the Iron Quadrangle (IQ), located in the central-southeastern portion of Minas Gerais State, stands out, covering approximately 7,000 km². This region is of considerable geological, economic, and environmental importance, characterized by significant mineral deposits, particularly iron, gold, and manganese, associated with Precambrian geological formations.[2] Mineral extraction has historically been one of the main drivers of land occupation and landscape transformation in the region, playing a fundamental role in the establishment and development of several urban settlements in Minas Gerais.

Historical occupation of the Iron Quadrangle intensified during the eighteenth-century gold rush, contributing to economic expansion and the establishment of important urban centers. Subsequently, iron ore extraction became one of the region's leading economic activities, accelerating landscape transformation and increasing the demand for infrastructure, natural resources, and land for productive activities.[3] This historical process established a complex relationship among economic development, territorial expansion, and environmental conservation, particularly in areas characterized by high ecological vulnerability.

From an environmental perspective, the Iron Quadrangle encompasses a wide diversity of ecosystems, including forest, savanna, and grassland formations, as well as ferruginous rocky grasslands, locally known as cangas. These environments exhibit relatively restricted geographical distributions, high floristic diversity, and the occurrence of endemic and threatened species. However, they are particularly vulnerable to transformations resulting from mineral extraction and other anthropogenic activities.[4] The ecological uniqueness of these environments, combined with increasing pressure on natural resources, makes the Iron Quadrangle a high-priority region for biodiversity conservation.[3,5,6]

The coexistence of intensive economic activities and environmentally sensitive ecosystems highlights the importance of Protected Areas (PAs) as instruments for territorial protection and the maintenance of ecological processes. According to the survey

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conducted by the Minas Gerais State Forestry Institute,[7] 45 Protected Areas were identified as being entirely or partially located within the boundaries of the Iron Quadrangle, corresponding to approximately 15% of the protected areas registered in Minas Gerais State in that survey. These areas represent important instruments for conserving remnants of native vegetation and protecting ecosystems exposed to varying levels of anthropogenic pressure.

In Brazil, the establishment and management of Protected Areas are primarily regulated by Federal Law No. 9,985 of July 18, 2000, which established the National System of Nature Conservation Units (Sistema Nacional de Unidades de Conservação da Natureza – SNUC). This system defines two main groups of Protected Areas: Strict Protection Areas, primarily intended for nature preservation and generally allowing only the indirect use of natural resources; and Sustainable Use Areas, which seek to reconcile environmental conservation with the sustainable use of certain natural resources.[8] The management of these areas involves different administrative levels, including federal, state, and municipal agencies. At the federal level, the Chico Mendes Institute for Biodiversity Conservation (Instituto Chico Mendes de Conservação da Biodiversidade – ICMBio) plays a central role, while the State Forestry Institute (IEF) is responsible for relevant management functions within Minas Gerais, in accordance with the responsibilities established by applicable legislation.[9]

Nevertheless, the existence of legal protection mechanisms does not, by itself, guarantee the maintenance of vegetation cover or the absence of environmental transformations within Protected Areas. Assessing LULC changes within these areas is therefore an important tool for identifying territorial alterations, recognizing potential anthropogenic pressures, and providing information to support environmental management. Comparing land transformation dynamics within Protected Areas with those observed in the surrounding regional context can improve understanding of landscape change processes. However, detecting land cover changes alone is insufficient to determine the ecological effectiveness of conservation measures.

In this context, advances in geotechnologies, particularly remote sensing and Geographic Information Systems (GIS), have expanded opportunities for environmental monitoring across different spatial and temporal scales. The integration of satellite imagery, cartographic databases, and spatial analysis tools enables the identification of land occupation patterns, the quantification of vegetation cover changes, and the monitoring of anthropogenic expansion. Furthermore, the increasing availability of open geospatial datasets and collaborative Earth observation platforms has contributed to broader access to environmental information and the development of research supporting land-use planning and territorial management.[10,11]

Among these initiatives, the MapBiomas Project stands out as a collaborative effort involving research institutions, nongovernmental organizations, and geotechnology specialists. The project provides historical time series of LULC maps derived from Landsat satellite imagery, enabling systematic analyses of territorial transformations throughout Brazil. Collection 6, released in 2021, covers the period from 1985 to 2020 at a spatial resolution of 30 m and constitutes the primary dataset used in this study.[12] The availability of these data enables investigations into the historical dynamics of LULC classes, including natural vegetation formations, agricultural activities, mining, forestry plantations, and urbanized areas.

Previous studies conducted in the Iron Quadrangle have demonstrated the diversity of scientific approaches used to investigate its environmental characteristics and the impacts of economic activities.[13] Examined the hydrogeochemical characteristics of surface waters, emphasizing the identification of pollution sources and the characterization of regional environmental conditions.[14] Investigated the historical evolution of mineral extraction in the Iron Quadrangle, drawing comparisons with mining experiences in European countries. In turn,[15] proposed a soil classification approach based on multivariate statistical techniques, including principal component analysis and k-means clustering, with applications related to the geotechnical characterization of soil materials.

Within the broader field of research on mining-related environmental impacts,[16] conducted a hypothetical economic assessment of environmental damage associated with the failure of a uranium mining tailings dam in Caldas, Minas Gerais, using an environmental resource economic valuation methodology. Their study considered potential damage to environmental components, including vegetation cover, demonstrating the importance of integrating territorial and environmental information when assessing the consequences of mining activities. Although conducted outside the Iron Quadrangle, this research provides a relevant contribution to understanding mining-related environmental impacts in Minas Gerais, particularly regarding the need to identify, characterize, and spatially assess potentially affected natural components.

Additionally,[17] examined environmental recovery measures for areas degraded by mining activities, emphasizing the importance of restoration and rehabilitation strategies in environments affected by mineral extraction. This perspective broadens the discussion of mining impacts by considering not only environmental degradation processes but also opportunities for recovering affected areas. Together, the studies by[16] and[17] reinforce the need to understand mining-induced landscape transformations and to develop tools capable of supporting environmental monitoring, identifying areas under anthropogenic pressure, and planning conservation and restoration measures.

Despite these contributions, further investigation into historical LULC transformations in the Iron Quadrangle and their manifestations within Protected Areas remains relevant. The studies address different dimensions of regional environmental issues, including hydrogeochemical characterization, mineral extraction, soil classification, environmental damage assessment, and the restoration of degraded areas. However, an integrated analysis of spatiotemporal LULC dynamics, combined with a comparison between the regional territory and legally protected areas, offers a complementary perspective for understanding landscape transformation processes. Assessing changes within Protected Areas belonging to different protection groups and administrative levels may help identify distinct patterns of territorial transformation and provide information relevant to environmental management.

Against this background, the overall objective of this study is to analyze the spatiotemporal dynamics of LULC in the Iron Quadrangle, Minas Gerais, Brazil, and within the Protected Areas located inside its boundaries, considering the period from 1985 to 2020. Specifically, the study aims to:

(i) Compile and organize geospatial data on LULC and the territorial boundaries of the Iron Quadrangle and its Protected Areas;

(ii) Apply geoprocessing procedures to delimit the study areas, process spatial information, and quantify LULC classes; and

(iii) Compare and discuss the identified territorial transformations, considering different land cover classes, protection groups, and administrative levels of Protected Areas.

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The findings are expected to contribute to a historical understanding of anthropogenic pressures on the regional landscape and provide information to support environmental monitoring and conservation in territories characterized by intensive mining activities.

Materials and methods

Study area – iron quadrangle

The study area encompasses the Iron Quadrangle (IQ), located in the central-southeastern portion of Minas Gerais State, Brazil, covering approximately 7,000 km² (Figure 1). The region is of considerable geological, economic, and environmental importance, characterized by the concentration of significant mineral deposits and a diversity of natural ecosystems. The coexistence of mining activities, urbanized areas, and remnants of native vegetation makes the Iron Quadrangle particularly relevant for investigating historical land use and land cover (LULC) changes. The selection of this region was based on its economic importance to Minas Gerais and the presence of environments characterized by high biological diversity and varying levels of anthropogenic pressure. These characteristics provide favorable conditions for analyzing territorial changes associated with the expansion of economic activities and ecosystem conservation, particularly within Protected Areas (PAs). The name Iron Quadrangle is associated with the geometric configuration of its geological and geomorphological structure. According to,[18] the term was introduced in 1933 by geologist Luiz Flores de Moraes Rego to describe the region containing major iron ore deposits in central Minas Gerais, as documented in his work entitled "As jazidas de ferro do centro de Minas Gerais" (The Iron Ore Deposits of Central Minas Gerais). This territorial configuration provides a historical and geographical reference for delimiting the study area and analyzing landscape transformations throughout the investigated period.

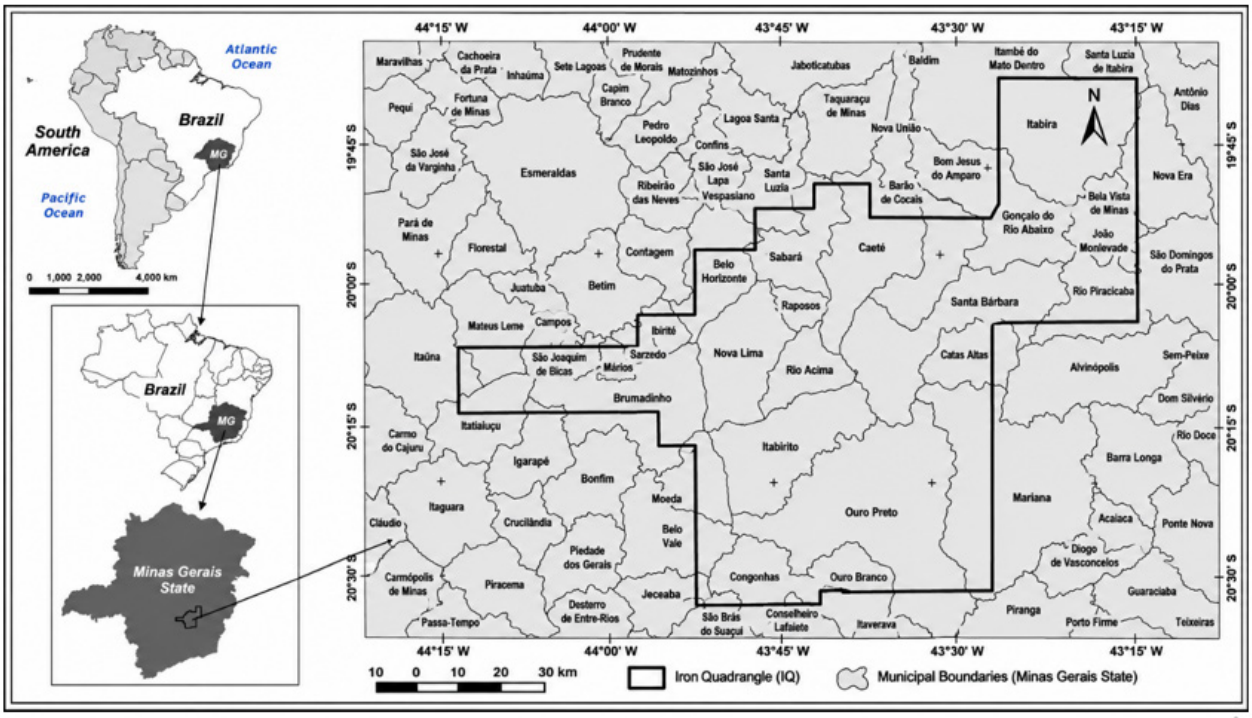

Figure 1 Geographical location of the Iron Quadrangle in Minas Gerais State, Brazil.

Source: Prepared by the authors (2026).

O The Iron Quadrangle is one of the world's classic Precambrian geological regions, characterized by complex geological structures and the occurrence of major mineral deposits. Its traditional geographical boundaries are approximately defined by lines connecting the municipalities of Itabira to the northeast, Mariana to the southeast, Congonhas to the southwest, and Itaúna to the northwest.[19] This spatial configuration, together with its lithological and geomorphological diversity, directly influences the characteristics of the terrain, drainage network, and distribution of natural ecosystems.

From a hydrographic perspective, the region includes headwater areas of two major Brazilian river basins: the São Francisco River Basin and the Doce River Basin. These basins play important roles in maintaining regional water resources, including the water supply of municipalities within the Belo Horizonte Metropolitan Region.[20] The geological and geomorphological configuration of the Iron Quadrangle influences the organization of its drainage network, contributing to the formation of deeply incised valleys, rapids, and waterfalls. These features are particularly evident along certain stretches of the Velhas River, where elevation gradients and geological structures influence fluvial morphology.[21]

The geological, geomorphological, and climatic diversity of the Iron Quadrangle supports the occurrence of different vegetation formations, distributed mainly across the Cerrado and Atlantic Forest phytogeographical domains. Atlantic Forest vegetation is represented by forest remnants exhibiting varying degrees of fragmentation and conservation, whereas the Cerrado comprises a mosaic of vegetation physiognomies, including forest, savanna, and grassland formations. These include riparian forests, gallery forests, cerradão (woodland savanna), cerrado sensu stricto (typical savanna), campo limpo (open grassland), and campo sujo (shrubby grassland), whose distribution is associated with local environmental conditions.[20]

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Among the region's most environmentally significant ecosystems are the rocky grasslands (campos rupestres), frequently associated with elevated terrain, rugged topography, and rocky outcrops. These vegetation formations occur predominantly at elevations above 900 m, on different geological substrates, including quartzites, iron-rich formations, and, locally, other lithologies. The associated soils are generally shallow, nutrient-poor, and characterized by low water-holding capacity, conditions that favor the development of specialized plant communities. Particularly important are the ferruginous rocky grasslands associated with ironstone outcrops known as cangas, which exhibit high ecological uniqueness and vulnerability to mining activities.[20]

From a socioeconomic perspective, the Iron Quadrangle is located within one of the most urbanized and economically dynamic regions of Minas Gerais, encompassing areas near the state capital, Belo Horizonte, and municipalities historically associated with mineral extraction. Mining is a major component of the regional economy, particularly through iron ore and gold extraction, contributing to employment generation, infrastructure expansion, and changes in land occupation patterns. According to the survey presented by,[20] based on information available at the time, the municipalities included in the regional analysis accounted for a substantial share of the state's population and economic output, highlighting the historical and socioeconomic importance of this territory.

Mineral extraction in the Iron Quadrangle has a long history associated with the occupation and development of Brazilian territory. During the gold mining cycle, particularly throughout the eighteenth and nineteenth centuries, the region became one of the country's main gold-producing centers. Subsequently, underground mining and the industrial exploitation of mineral deposits consolidated its regional economic importance. Between 1900 and 1930, for example, Brazilian gold production reached approximately 121 metric tons, of which about 114 metric tons originated from the Morro Velho Mine, located in the municipality of Nova Lima. Between 1930 and 1977, this mining operation continued to account for a substantial share of national gold production, demonstrating the region's historical importance to Brazil's mining sector.[22]

The economic significance of mining activities is also reflected in historical surveys of gold and iron ore production. According to,[20] based on data from the Brazilian Mining Institute for 2008, Minas Gerais accounted for approximately 39.7% of Brazilian gold production that year. During the same period, the Iron Quadrangle also made a substantial contribution to national iron ore production, reinforcing its status as a major mineral province. These historical indicators demonstrate the intensity of extractive activities and their influence on regional economic and territorial dynamics, although they should not be interpreted as representative of current conditions.

The combination of economic importance, ecosystem diversity, legally protected areas, and a long history of mineral extraction makes the Iron Quadrangle particularly suitable for investigating LULC changes. In this context, the multitemporal analysis covering 1985 to 2020 enables the identification of historical patterns of anthropogenic expansion and vegetation transformation, providing a spatial basis for comparing changes observed across the regional territory and within its Protected Areas.

Study area – protected areas

To analyze land use and land cover (LULC) changes, the study considered Protected Areas (PAs) located entirely or partially within the geographical boundaries of the Iron Quadrangle (IQ), Minas Gerais State, Brazil. These areas were selected to investigate land transformations within legally protected territories and their relationship with regional land occupation dynamics, particularly in a context characterized by mining activities, urban expansion, and other forms of anthropogenic land use.

Protected Areas are legally designated geographical spaces, including their environmental resources and waters under the relevant jurisdiction, characterized by significant natural features and subject to specific protection and management regimes. In Brazil, these areas are regulated by Federal Law No. 9,985 of July 18, 2000, which established the National System of Nature Conservation Units (*Sistema Nacional de Unidades de Conservação da Natureza* – SNUC), defining criteria and regulations for their establishment, implementation, and management.[8]

The SNUC encompasses Protected Areas administered at the federal, state, and municipal levels, organized into 12 management categories distributed across two main groups: Strict Protection and Sustainable Use. According to Article 7 of Law No. 9,985/2000, the primary objective of Strict Protection Areas is to preserve nature, generally allowing only the indirect use of natural resources, except as otherwise provided by law. Sustainable Use Areas, in turn, seek to reconcile nature conservation with the sustainable use of a portion of their natural resources.[8]

The management of Protected Areas is carried out by the competent authorities at each administrative level. At the federal level, the Chico Mendes Institute for Biodiversity Conservation (*Instituto Chico Mendes de Conservação da Biodiversidade* – ICMBio) plays a central role. In Minas Gerais, the State Forestry Institute (*Instituto Estadual de Florestas* – IEF) performs functions related to the establishment, implementation, protection, and management of state-level Protected Areas, in accordance with applicable legislation. Municipal Protected Areas are managed by their respective local government authorities.

According to the survey conducted by the State Forestry Institute,[7] 295 Protected Areas were identified in Minas Gerais State, of which 170 belonged to the Sustainable Use group and 125 to the Strict Protection group. This distribution demonstrates the existence of different territorial protection instruments, characterized by distinct management objectives and land use restrictions. The geographical distribution of the Protected Areas included in this survey is presented in Figure 2.

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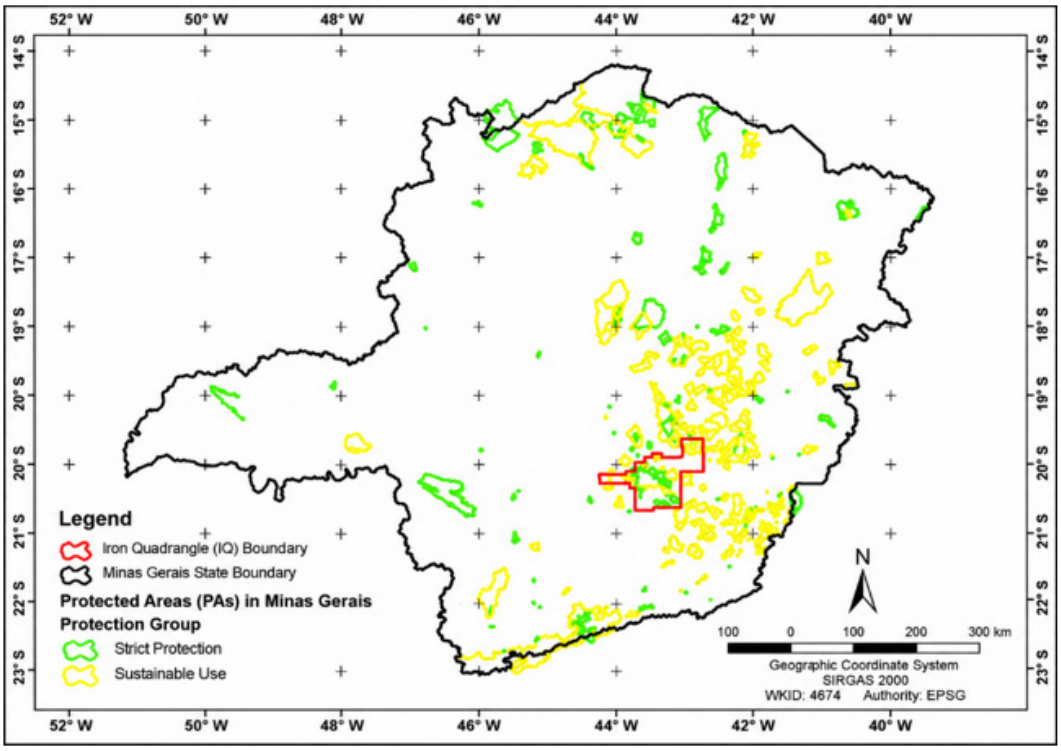

Figure 2 Spatial distribution of Protected Areas in Minas Gerais State, Brazil.

Source: Adapted from.[7]

The distribution of Protected Areas by protection group and their corresponding territorial extent is presented in Figure 3. This representation characterizes the composition of the state's protected area network, considering both the number of designated areas and their respective surface areas.

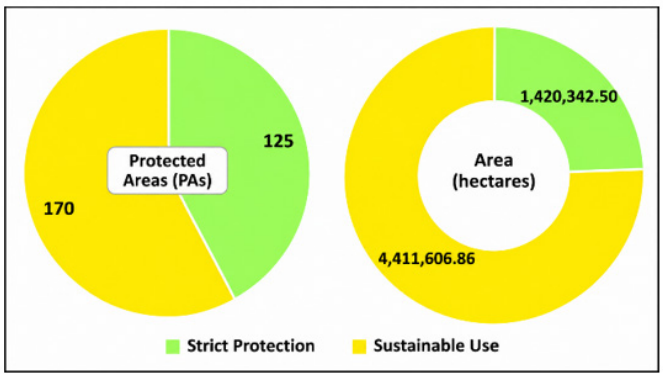

Figure 3 Distribution of Protected Areas in Minas Gerais State by protection group and territorial area, expressed in hectares.

Source: Adapted from.[7]

In addition to their classification by protection group, Protected Areas fall under different administrative jurisdictions, an important aspect for understanding the institutional organization of environmental protection throughout the state. Figure 4 presents the distribution of protected land, expressed in hectares, according to protection group and administrative level, allowing the relative contributions of federal, state, and municipal Protected Areas to the state's protected territory to be identified.

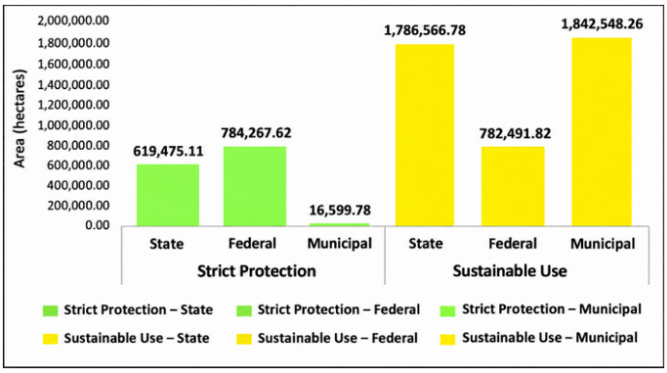

Figure 4 Distribution of Protected Area coverage in Minas Gerais State by protection group and administrative level, expressed in hectares.

Source: Adapted from.[7]

Within the geographical boundaries of the Iron Quadrangle, 45 Protected Areas were identified based on the survey and spatial boundaries adopted in this study. These areas encompass different management categories and administrative levels, enabling a comparative investigation of LULC changes in territories subject to different environmental protection regimes.

The spatial analysis considered only the areas within the official boundaries of the Protected Areas, excluding their respective buffer zones. This delimitation enabled the quantification of LULC classes within legally protected territories and the comparison of their changes with those observed across the Iron Quadrangle from 1985 to 2020. Accordingly, the analysis sought to characterize land transformation dynamics within Protected Areas and identify potential anthropogenic

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pressures, without assuming that the observed changes alone constitute conclusive indicators of conservation effectiveness.

Advanced geoprocessing workflow

Following the delineation of the study area and the identification of Protected Areas (PAs) located within the boundaries of the Iron Quadrangle (IQ), systematic procedures were implemented for the acquisition, organization, preprocessing, and analysis of geospatial data. These procedures aimed to characterize land use and land cover (LULC) changes over the period from 1985 to 2020. The methodological workflow was structured into nine sequential stages, as illustrated in the flowchart presented in Figure 5. These stages included the acquisition of cartographic datasets and thematic data, the preparation and harmonization of spatial information, the implementation of geoprocessing operations, and the extraction of quantitative information on LULC classes. These procedures enabled the organization of the information required for the multitemporal analysis of the Iron Quadrangle and the comparative assessment of changes identified within Protected Areas, considering their respective protection groups and administrative levels. The results of the spatial processing operations and quantitative analyses are presented and discussed in the corresponding sections of this article.

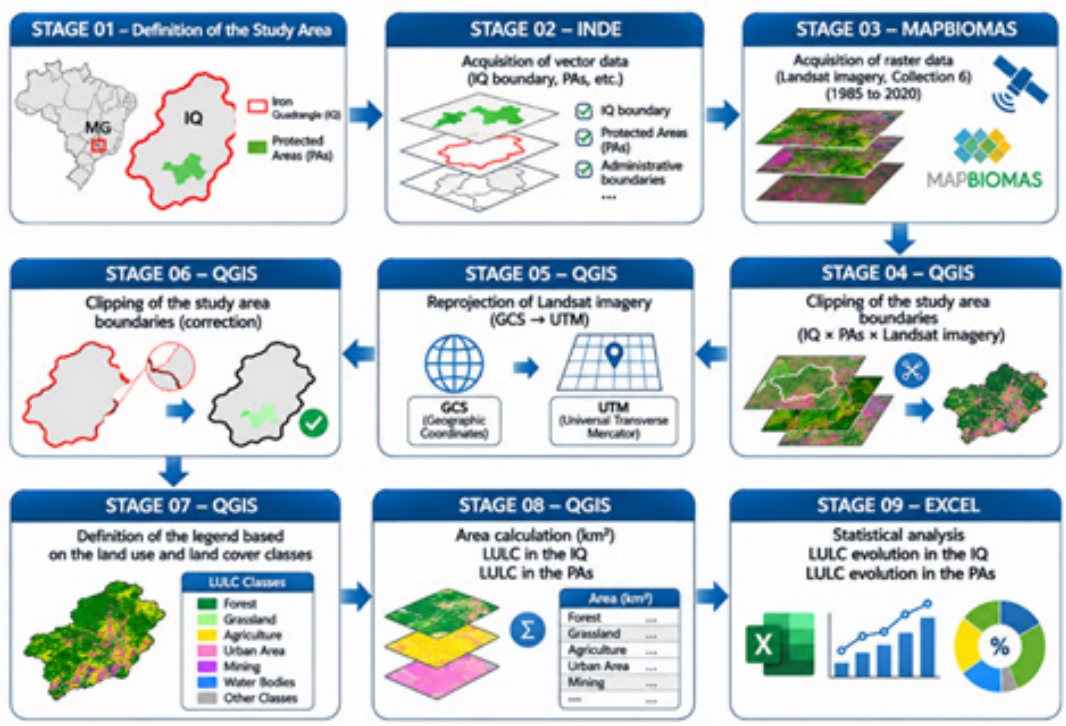

Figure 5 Flowchart illustrating the methodological stages of geospatial data acquisition, preprocessing, processing, and analysis.

Source: Prepared by the authors (2026).

Stage 2 – Acquisition of vector data: Geographic boundaries

The vector datasets used to delineate the study areas were obtained through the Brazilian National Spatial Data Infrastructure (Infraestrutura Nacional de Dados Espaciais – INDE), using the geoservices catalog of the Spatial Data Infrastructure of the Minas Gerais State Environmental and Water Resources System (IDE-Sisema), Brazil. Geospatial data were acquired through the Web Feature Service (WFS), which enables access to and retrieval of geographic features provided by spatial data servers. Three main vector datasets were obtained:

(i) The administrative boundary of Minas Gerais State;

(ii) The boundaries of Protected Areas (PAs) located within the state; and

(iii) The geographic boundary of the Iron Quadrangle (IQ).

These datasets provided the spatial reference for subsequent procedures involving territorial delineation, selection of Protected Areas, and analysis of land use and land cover (LULC) changes.

The WFS standard, developed by the Open Geospatial Consortium (OGC), defines specifications for querying and accessing geographic features through interoperable services. According to INDE (2022), this service enables the retrieval of vector geospatial information, including representations in Geography Markup Language (GML), through requests submitted by GIS applications or other compatible clients. Its use facilitates the integration of information from different institutions and the standardization of geospatial data acquisition procedures. The vector datasets were originally provided in the Geocentric Reference System for the Americas 2000 (SIRGAS 2000), using geographic coordinates (EPSG:4674). Subsequently, the datasets were reprojected into the SIRGAS 2000 / UTM Zone 23S projected coordinate reference system (EPSG:31983), using QGIS software, version 3.6.2 (Noosa).[23] The adoption of a projected coordinate reference system, with coordinates expressed in meters, aimed to ensure spatial compatibility among the vector datasets and support the geoprocessing operations and area calculations used to quantify LULC classes. Accordingly, the datasets were prepared for subsequent spatial clipping procedures, integration with thematic information, and multitemporal analysis of the Iron Quadrangle and the selected Protected Areas.

Stage 3 – Acquisition of raster data: Satellite imagery and land cover

Raster land use and land cover (LULC) data constituted the primary thematic dataset used in this study, providing the basis for identifying and quantifying land transformations in the Iron Quadrangle (IQ) and the Protected Areas (PAs) located within its boundaries. The data were obtained from Collection 6 of the MapBiomas Project, released in August 2021, covering the annual historical time series from 1985 to 2020, corresponding to 36 years of observations.

According to,[12] annual LULC maps are produced through the classification of imagery acquired by the Landsat satellite series, with a spatial resolution of 30m. The processing workflow implemented by the project uses satellite image mosaics generated through the spatial and temporal integration of selected observations, considering criteria related to pixel quality, cloud cover, and the spectral characteristics of the Earth's surface.

The composition of these mosaics accounts for the environmental and phenological characteristics of different Brazilian biomes, allowing the selection of temporal periods and spectral information suitable for identifying LULC classes. The mosaics may incorporate multiple variables, including spectral bands, fractions, and image-derived indices, such as the Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Fraction Index (NDFI), which are used as auxiliary information in the thematic classification procedures developed by MapBiomas.[12]

For this study, the datasets were accessed through the Google Earth Engine (GEE) platform using products made available by the MapBiomas Project. Annual thematic maps covering the period from 1985 to 2020 were obtained, totaling 36 raster datasets, individually organized by year to support subsequent spatial clipping, class area quantification, and multitemporal comparison procedures.

The thematic maps contain categorical values representing different LULC classes, enabling the identification of natural vegetation formations and areas affected by anthropogenic activities, such as mining, forestry plantations, and urbanization. These datasets provided the basis for the quantitative analysis of land transformations observed in the Iron Quadrangle and its Protected Areas, following the geoprocessing procedures described in the subsequent methodological stages.

Stage 4 – Spatial clipping of land use and land cover data in the iron quadrangle and protected areas

Following the acquisition of vector and raster datasets, the next methodological stage involved spatially clipping the thematic land use and land cover (LULC) maps from MapBiomas Collection 6 using the geographic boundaries of the Iron Quadrangle (IQ) and its Protected Areas (PAs) as clipping masks. This procedure was performed using QGIS software, version 3.6.2 (Noosa),[23] with both vector and raster datasets referenced to the same coordinate reference system (CRS). The initial clipping operations were conducted using the original geographic coordinate reference system, SIRGAS 2000 (EPSG:4674). Figure 6 and Figure 7 illustrate the spatial clipping procedures.

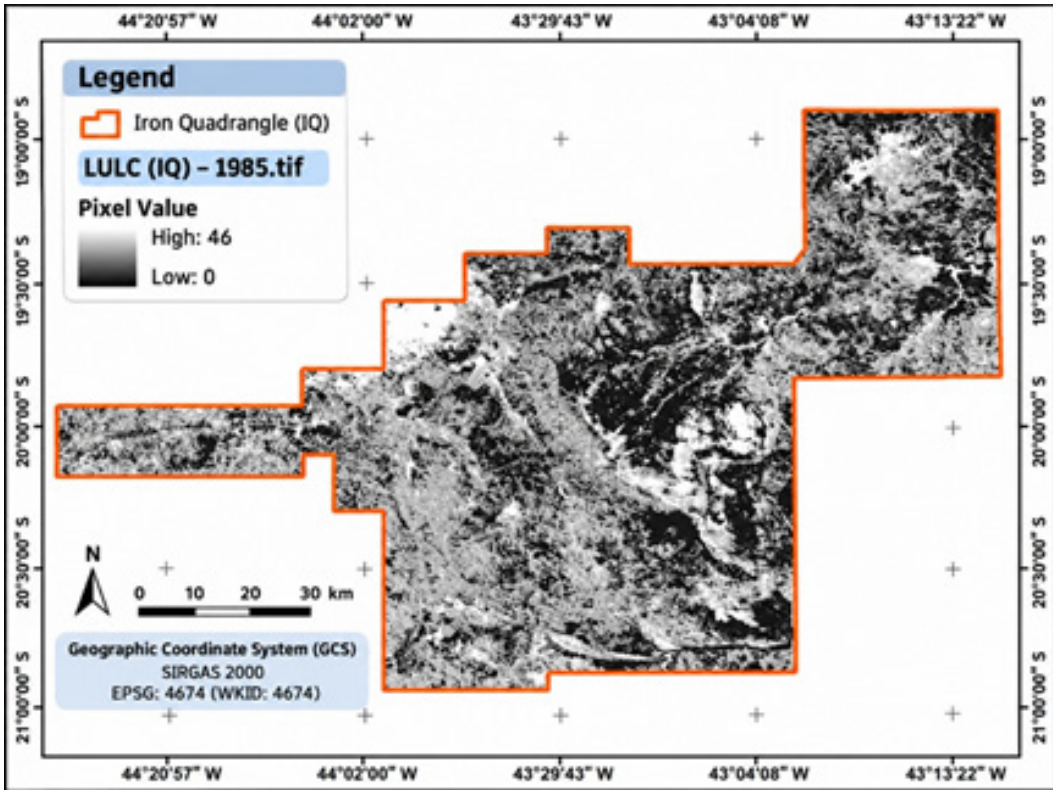

Figure 6 Spatial clipping of the MapBiomas Collection 6 land use and land cover raster (1985) using the geographic boundary of the Iron Quadrangle as a clipping mask.

Source: Prepared by the authors (2026).

Citation: Nero MA, Palhares AA. Spatiotemporal dynamics of land use and land cover in the iron quadrangle and its protected areas from 1985 to 2020. *MOJ Eco Environ Sci.* 2026;11(6):182–201. DOI: 10.15406/mojes.2026.11.00401

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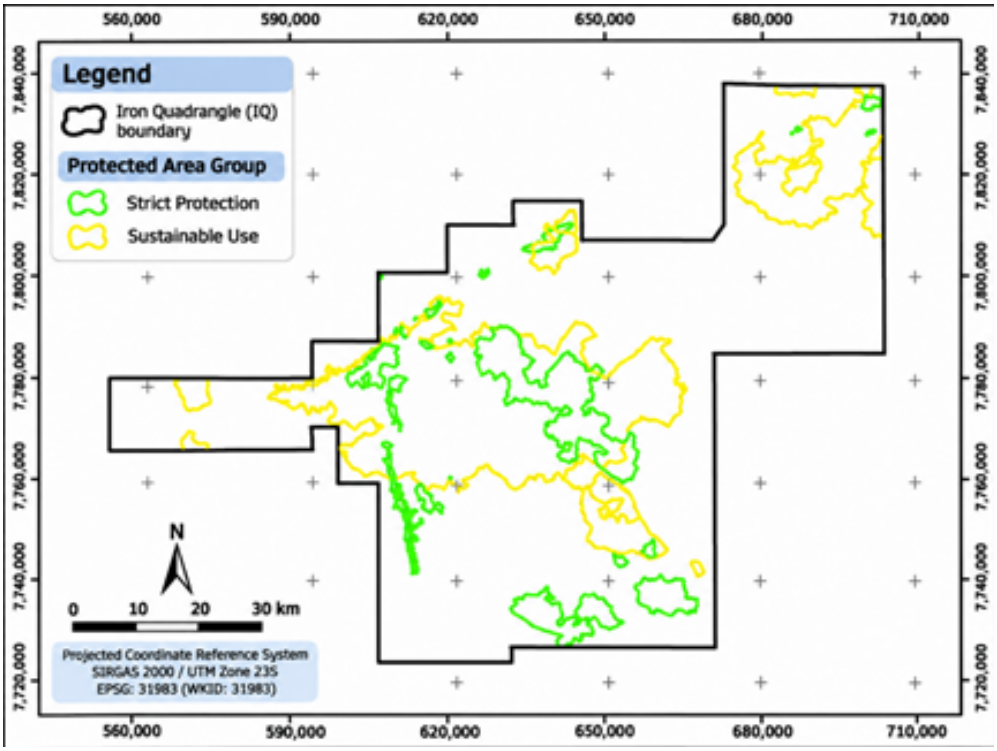


Figure 7 Spatial distribution of Protected Areas within the Iron Quadrangle, classified into Strict Protection and Sustainable Use groups.

Source: Prepared by the authors (2026).

A total of 36 spatial clipping operations were performed, corresponding to one annual thematic raster for each year between 1985 and 2020. The resulting datasets were stored in a dedicated project directory for subsequent geoprocessing operations, including reprojection into a metric coordinate reference system and area calculations.

This procedure also enabled the identification of Protected Areas located within the Iron Quadrangle. Of the 295 Protected Areas recorded in the state of Minas Gerais, 45 (approximately 15%) were identified within the Iron Quadrangle, as illustrated in the central portion of Figure 7 and further represented in Figure 8.

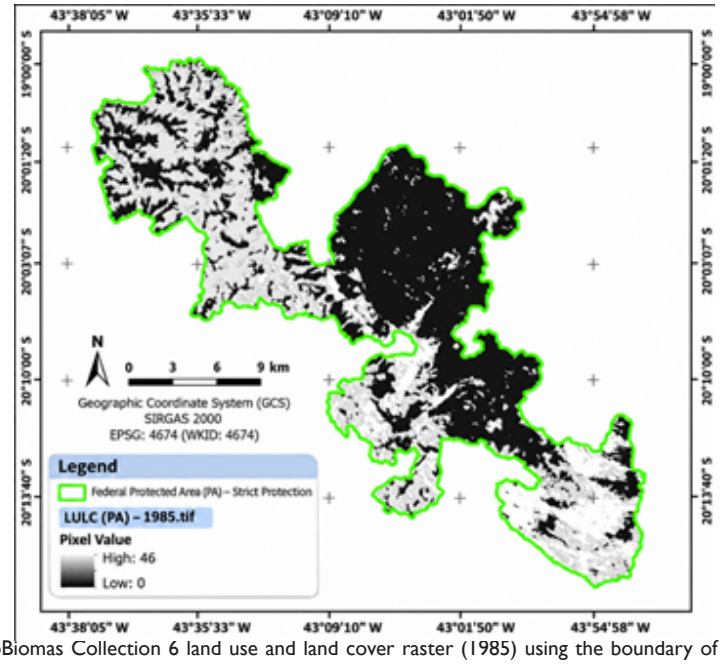


Figure 8 Spatial clipping of the MapBiomas Collection 6 land use and land cover raster (1985) using the boundary of a Federal Strict Protection Area as a clipping mask.

Source: Prepared by the authors (2026).

Citation: Nero MA, Palhares AA. Spatiotemporal dynamics of land use and land cover in the iron quadrangle and its protected areas from 1985 to 2020. *MOJ Eco Environ Sci.* 2026;11(6):182–201. DOI: 10.15406/mojes.2026.11.00401

Figure 9 and Figure 10 provide a more detailed characterization of the distribution of Protected Areas within the Iron Quadrangle, considering their protection groups, spatial extent, and administrative jurisdiction. For the analysis of LULC changes within Protected Areas, two additional temporal clipping datasets were generated, corresponding to the initial (1985) and final (2020) years of the study period. The resulting raster datasets were stored in a dedicated project directory for subsequent processing, including reprojection into a metric coordinate reference system and calculation of the areas occupied by the different LULC classes.

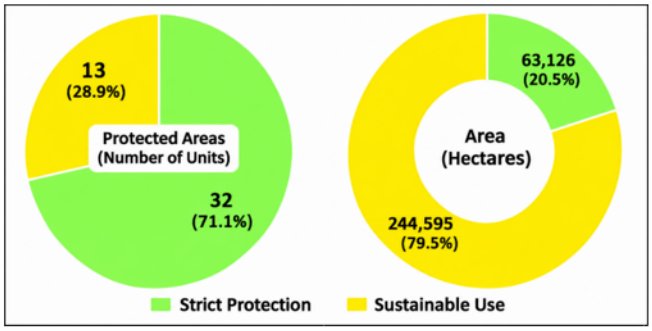


Figure 9 Distribution of Protected Areas in the Iron Quadrangle by protection group, number of units, and total area (ha).

Source: Adapted from.[7]

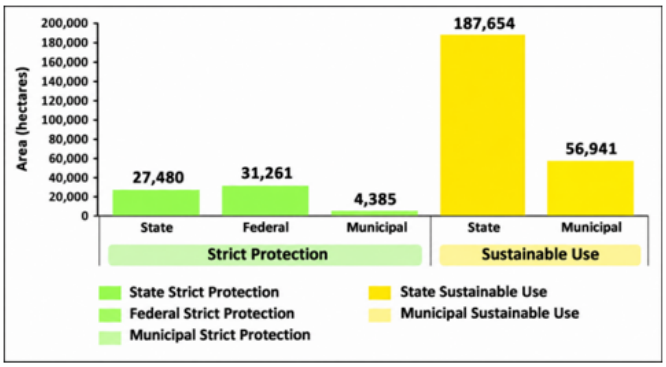


Figure 10 Distribution of Protected Area extent (ha) in the Iron Quadrangle by protection group and administrative jurisdiction.

Source: Adapted from.[7]

Stage 5 – Reprojection of clipped satellite-derived raster data

Following the spatial clipping of the satellite-derived raster datasets and the geographic boundaries of the study areas, both vector and raster datasets were reprojected into a projected coordinate reference system to enable area calculations in metric units. This procedure was performed using QGIS software, version 3.6.2 (Noosa),[23] adopting SIRGAS 2000 / UTM Zone 23S (EPSG:31983) as the target coordinate reference system (CRS). During raster reprojection, the nearest-neighbor resampling method was manually selected to preserve the original categorical land use and land cover codes of MapBiomas Collection 6[12] and prevent the generation of intermediate class values. The output pixel resolution was also manually set to 30 × 30 m, maintaining the nominal spatial resolution of the original MapBiomas datasets.

Stage 6 – Spatial clipping of reprojected raster data

Following the reprojection of vector and raster datasets into the SIRGAS 2000/UTM Zone 23S coordinate reference system, minor distortions were observed along the boundaries of the output rasters, resulting in unwanted pixels containing null values (NoData). To eliminate these pixels and prevent potential interference with subsequent area calculations, an additional spatial clipping procedure was performed on all raster datasets, using the geographic boundaries of the Iron Quadrangle (IQ) and the selected Protected Areas (PAs) as clipping masks. Unlike the initial clipping operation, this procedure was conducted in the target projected coordinate reference system, ensuring spatial consistency between the raster datasets and the corresponding vector boundaries. For Protected Areas extending beyond the boundaries of the Iron Quadrangle, only the portions located within the IQ were considered in the spatial analyses. Accordingly, the boundaries of these Protected Areas were spatially clipped to the IQ boundary before being used as masks for raster extraction. This procedure ensured that the LULC analyses and subsequent area calculations were restricted to the portions of the selected Protected Areas located within the Iron Quadrangle.

Stage 7 – Assignment of land use and land cover classes to reprojected and clipped raster data

The identification of land use and land cover (LULC) classes was performed according to the classification legend provided by the MapBiomas Project,[12] as detailed in Table 1. This legend establishes the correspondence between the numerical pixel values in the MapBiomas Collection 6 raster datasets, their respective LULC classes, and the hexadecimal color codes used for thematic visualization in Geographic Information System (GIS) software, including ArcMap[24] and QGIS.[23]

Table 1 Land use and land cover classification codes and corresponding hexadecimal colors from MapBiomas Collection 6

Class code	Hexadecimal	Color	First-level class	Second-level class
0	Null	Null	Null	Null
3	6400		Forest	Forest Formation
4	00ff00		Forest	Savanna Formation
9	ad4413		Farming	Forest Plantation
11	45C2A5		Non-Forest Natural Formation	Wetland
12	B8AF4F		Non-Forest Natural Formation	Grassland Formation
15	FFD966		Farming	Pasture
21	fff3bf		Farming	Mosaic of Agriculture and Pasture
24	aa0000		Non-Vegetated Area	Urban Area
25	ff3d3d		Non-Vegetated Area	Other Non-Vegetated Areas
29	665a3a		Non-Forest Natural Formation	Rocky Outcrop
30	af2a2a		Non-Vegetated Area	Mining
33	0000FF		Water Body	River, Lake, and Ocean
46	cca0d4		Farming	Coffee/Agriculture

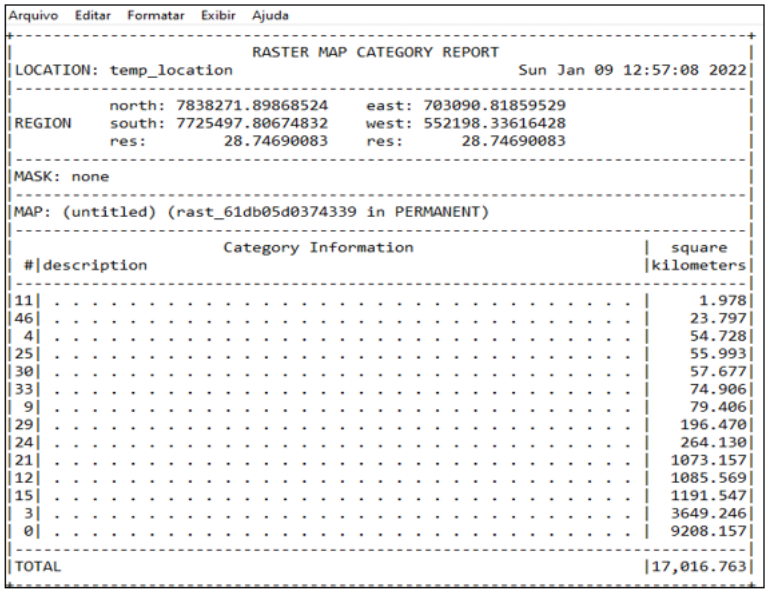
Source: Adapted from.[12]

Using these legend codes, each pixel within the raster datasets clipped to the boundaries of the Iron Quadrangle (IQ) and the selected Protected Areas (PAs) was associated with its corresponding LULC class. This procedure enabled the identification and spatial representation of the thematic classes, providing the basis for subsequent area calculations and multitemporal analyses.

Stage 8 – Calculation of land use and land cover areas

The areas occupied by the different land use and land cover (LULC) classes were calculated using the r.report raster geoprocessing tool available through GRASS GIS, version 7.6.1,[25] integrated into QGIS software, version 3.6.2 (Noosa).[23] According to,[25] the *r.report* tool calculates raster category areas based on pixel dimensions and presents the resulting statistics in tabular format. The command allows users to configure a range of reporting parameters for a raster map and generate customized statistical reports. The *r.report* tool enables users to specify the measurement units in which the statistics are reported. This functionality provides a practical alternative to converting raster datasets into vector polygons (polygonization), particularly when computational resources and processing time are limited. Furthermore, the resulting reports can be formatted for subsequent import into Microsoft Excel spreadsheets, facilitating data organization, interpretation, and quantitative analysis.

Each report consists of two main components: a header section and a statistical body. The header identifies the raster map, including its name and title, location, mapset, date, and region of interest. The spatial extent is described through the current computational region and, when applicable, the active raster mask. The main body contains one to three tables presenting the statistics associated with each raster category and the corresponding totals for each selected measurement unit. All statistics are calculated within the current computational region. Figure 11 illustrates an example of the statistical report generated by the tool.



```
Arquivo  Editar  Formatar  Exibir  Ajuda
+-----------------------------------------------------------------------------+
|                         RASTER MAP CATEGORY REPORT                          |
|LOCATION: temp_location                              Sun Jan 09 12:57:08 2022|
|-----------------------------------------------------------------------------|
|          north: 7838271.89868524    east: 703090.81859529                   |
|REGION    south: 7725497.80674832    west: 552198.33616428                   |
|          res:        28.74690083    res:      28.74690083                   |
|-----------------------------------------------------------------------------|
|MASK: none                                                                   |
|-----------------------------------------------------------------------------|
|MAP: (untitled) (rast_61db05d0374339 in PERMANENT)                           |
|-----------------------------------------------------------------------------|
|                      Category Information                        |  square  |
| #|description                                                    |kilometers|
|-----------------------------------------------------------------------------|
|11| . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . |     1.978|
|46| . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . |    23.797|
| 4| . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . |    54.728|
|25| . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . |    55.993|
|30| . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . |    57.677|
|33| . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . |    74.906|
| 9| . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . |    79.406|
|29| . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . |   196.470|
|24| . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . |   264.130|
|21| . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . |  1073.157|
|12| . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . |  1085.569|
|15| . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . |  1191.547|
| 3| . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . |  3649.246|
| 0| . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . |  9208.157|
|-----------------------------------------------------------------------------|
|TOTAL                                                             |17,016.763|
+-----------------------------------------------------------------------------+
```

Figure 11 Example of a raster statistical report generated in tabular format using the GRASS GIS *r.report* tool [25].

Source: Prepared by the authors (2026).

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The *r.report* command was applied to the 36 annual LULC raster datasets covering the Iron Quadrangle (IQ) from 1985 to 2020. For the Protected Areas (PAs), 10 additional reports were generated, corresponding to the initial (1985) and final (2020) years of the study period. These reports were organized according to the protection group and administrative jurisdiction of the PAs, as summarized in Table 2.

Table 2 Summary of statistical reports generated to assess land use and land cover changes in the Iron Quadrangle and its Protected Areas

Study area	Description	Study period
Iron Quadrangle (IQ)	36 annual statistical reports	1985–2020
Protected Areas (PAs)	10 statistical reports distributed as follows:	1985 and 2020
Municipal Protected Areas	2 – Strict Protection	1985 and 2020
	2 – Sustainable Use	1985 and 2020
State Protected Areas	2 – Strict Protection	1985 and 2020
	2 – Sustainable Use	1985 and 2020
Federal Protected Areas	2 – Strict Protection	1985 and 2020
Total	46 statistical reports	1985–2020

Source: Prepared by the authors (2026).

For the calculation of the percentage distribution of LULC classes, the area occupied by each thematic class was divided by the total area of valid LULC classes within the corresponding spatial unit and multiplied by 100. Pixels classified as Null/NoData (code 0) were excluded from the denominators. Separate denominators were adopted for the Iron Quadrangle and for each group of Protected Areas, according to their protection categories and administrative jurisdictions. For Protected Areas extending beyond the Iron Quadrangle, only the portions located within the IQ boundaries were considered, as described in Stage 6. This procedure ensured that the calculated percentages represented the relative distribution of valid LULC classes within their respective territorial units.

Stage 9 – Assessment of land use and land cover changes

The assessment of land use and land cover (LULC) changes was conducted using Microsoft Excel, version 2201 (2022 build).[26] The analysis involved comparing increases and decreases in the area occupied by each LULC class within the Iron Quadrangle (IQ) and its Protected Areas (PAs), considering the selected temporal periods and the area measurements obtained through the preceding geoprocessing procedures.

The percentage change for each LULC class between 1985 and 2020 was calculated by dividing the difference between the final and initial class areas by the corresponding class area in 1985 and multiplying the result by 100. Thus, the initial area of each thematic class was adopted as the denominator for calculating its relative temporal change.

This approach enabled the identification and quantification of temporal changes in the spatial extent of individual LULC classes, providing the basis for evaluating land cover dynamics across the study area. The corresponding results are presented and discussed in a dedicated section of this study.

Limitations associated with the MapBiomas Collection 6[12] datasets were also considered when interpreting the LULC changes. The nominal spatial resolution of 30 m may restrict the identification of small or spatially fragmented land cover features, particularly within Protected Areas containing heterogeneous landscapes. Furthermore, thematic classification uncertainties may affect the differentiation of certain LULC classes and the estimation of their respective areas. Consequently, the observed changes should be interpreted considering the spatial resolution and thematic accuracy limitations of the original MapBiomas[12] datasets, particularly when assessing relatively small changes or transitions between spectrally similar classes.

Results and discussion

Assessment of land use and land cover changes in the iron quadrangle

The results of the land use and land cover (LULC) change assessment in the Iron Quadrangle (IQ) are presented in Table 3 and illustrated in Figure 12. These results provide a quantitative overview of the changes observed across the different LULC classes over the 36-year study period, from 1985 to 2020.

Table 3 Changes in land use and land cover in the Iron Quadrangle over the 36-year period (1985–2020)

Class code	Hexadecimal	Color	Second-level LULC class	1985 (ha)	2020 (ha)	Change (ha)	Change (%)
3	6400		Forest Formation	364,924.60	346,290.10	-18,634.50	-5%
4	00ff00		Savanna Formation	5,472.80	7,661.60	2,188.80	40%
9	ad4413		Forest Plantation	7,940.60	29,975.90	22,035.30	278%
11	45C2A5		Wetland	197.8	141.1	-56.7	-29%
12	B8AF4F		Grassland Formation	108,556.90	110,234.80	1,677.90	2%
15	FFD966		Pasture	119,154.70	96,135.90	-23,018.80	-19%
21	fff3bf		Mosaic of Agriculture and Pasture	107,315.70	98,866.60	-8,449.10	-8%
24	aa0000		Urban Area	26,413.00	40,351.20	13,938.20	53%
25	ff3d3d		Other Non-Vegetated Areas	5,599.30	3,437.30	-2,162.00	-39%
29	665a3a		Rocky Outcrop	19,647.00	21,188.80	1,541.80	8%
30	af2a2a		Mining	5,767.70	21,495.90	15,728.20	273%
33	0000FF		River, Lake, and Ocean	7,490.60	4,193.30	-3,297.30	-44%
46	cca0d4		Coffee/Agriculture	2,379.70	888.2	-1,491.50	-63%

Source: Prepared by the authors (2026).

Citation: Nero MA, Palhares AA. Spatiotemporal dynamics of land use and land cover in the iron quadrangle and its protected areas from 1985 to 2020. *MOJ Eco Environ Sci.* 2026;11(6):182–201. DOI: 10.15406/mojes.2026.11.00401

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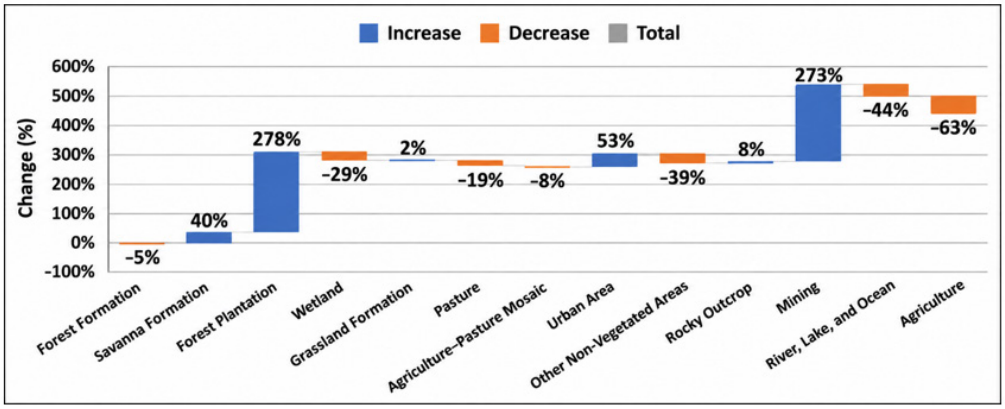

Figure 12 Percentage changes in land use and land cover classes in the Iron Quadrangle between 1985 and 2020.

Source: Prepared by the authors (2026).

As shown in Table 3 and Figure 12, the Iron Quadrangle experienced substantial expansion of land cover classes associated with economic development between 1985 and 2020. Forest plantations increased by 278%, mining areas by 273%, and urban areas by 53%. Among the land cover classes potentially associated with biodiversity conservation, savanna formations increased by 40%, while rocky outcrops increased by 8%. Conversely, the most pronounced reductions were observed in agriculture (-63%) and surface water bodies, represented by the River, Lake, and Ocean class (-44%). Despite the substantial expansion of economic activities, forest plantations (3.84%), mining (2.75%), and urban areas (5.17%) collectively accounted for only 11.76% of the total mapped LULC area in the Iron Quadrangle in 2020, as illustrated in Figure 13. These classes occupied the fifth, sixth, and seventh positions, respectively, in the overall ranking of LULC classes by area. Together, they represent important land cover categories associated with economic activities in the study region.

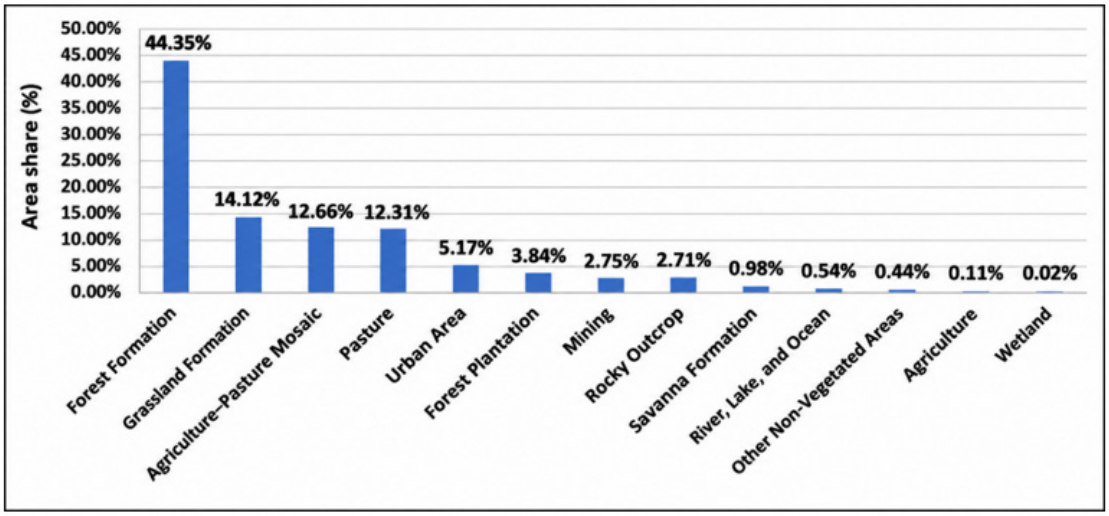

Figure 13 Percentage distribution of land use and land cover classes in the Iron Quadrangle in 2020.

Source: Prepared by the authors (2026).

When forest, grassland, and savanna formations, rocky outcrops, surface water bodies (rivers, lakes, and oceans), and wetlands are considered together, these classes account for 62.71% of the total area of the Iron Quadrangle. Their predominance indicates that land cover classes associated with natural ecosystems and biodiversity conservation continue to occupy a substantial proportion of the study area, despite the expansion of mining, forestry plantations, and urban development.

Assessment of land use and land cover changes in protected areas within the iron quadrangle

The results of the land use and land cover (LULC) change assessment in Protected Areas (PAs) located within the Iron Quadrangle (IQ) are presented in the following tables and figures, considering both the protection group and administrative jurisdiction. The analysis distinguishes between Strict Protection and Sustainable Use Areas administered at the municipal, state, and federal levels.

Citation: Nero MA, Palhares AA. Spatiotemporal dynamics of land use and land cover in the iron quadrangle and its protected areas from 1985 to 2020. *MOJ Eco Environ Sci.* 2026;11(6):182–201. DOI: 10.15406/mojes.2026.11.00401

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The results for municipally administered Strict Protection Areas over the 36-year study period (1985–2020) are presented first, in Table 4 and Figure 14.

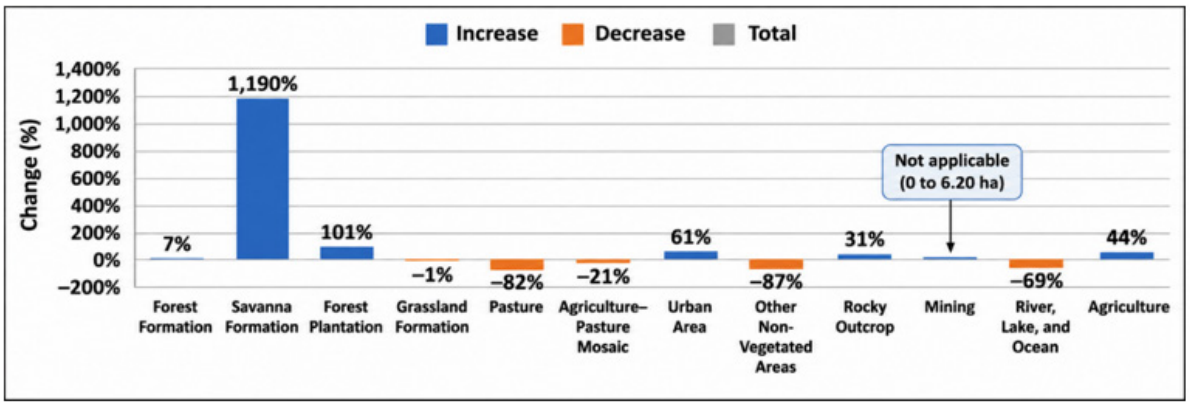

Figure 14 Percentage changes in land use and land cover classes in municipally administered Strict Protection Areas within the Iron Quadrangle between 1985 and 2020.

Source: Prepared by the authors (2026).

Table 4 Changes in land use and land cover in municipally administered Strict Protection Areas over the 36-year period (1985–2020)

Class code	Hexadecimal	Color	Second-level LULC class	1985 (ha)	2020 (ha)	Change (ha)	Change (%)
3	006400		Forest Formation	1,496.75	1,594.51	97.76	+7%
4	00ff00		Savanna Formation	1.98	25.54	23.56	+1,190%
9	ad4413		Forest Plantation	1.98	3.97	1.99	+101%
12	B8AF4F		Wetland	2,241.07	2,213.22	-27.85	-1%
15	FFD966		Grassland Formation	103.30	18.76	-84.54	-82%
21	fff3bf		Mosaic of Agriculture and Pasture	338.57	266.59	-71.98	-21%
24	aa0000		Urban Area	47.35	76.03	28.68	+61%
25	ff3d3d		Other Non-Vegetated Areas	15.95	2.07	-13.88	-87%
29	665a3a		Rocky Outcrop	127.43	167.34	39.91	+31%
30	af2a2a		Mining	0.00	6.20	6.20	-
33	0000FF		River, Lake, and Ocean	2.15	0.66	-1.49	-69%
46	cca0d4		Coffee/Agriculture	3.72	5.37	1.65	+44%

Source: Prepared by the authors (2026).

As shown in Table 4 and Figure 14, municipally administered Strict Protection Areas experienced considerable changes in LULC over the 36-year study period. Among the classes associated with economic activities, mining expanded from no mapped area in 1985 to 6.20 ha in 2020, while forest plantations and urban areas increased by 101% and 61%, respectively. Among the classes potentially associated with biodiversity conservation, savanna formations exhibited a substantial relative increase of 1,190%, while rocky outcrops expanded by 31%. Conversely, reductions were observed in grassland formations (−1%) and surface water bodies, represented by the River, Lake, and Ocean class (−69%).

Despite the substantial expansion of economic activities, particularly mining, forest plantations, and urban development, these three LULC classes collectively accounted for only 1.97% of the total area of municipally administered Strict Protection Areas in 2020, as illustrated in Figure 15. Urban areas, mining, and forest plantations ranked fifth, eighth, and tenth, respectively, among the mapped LULC classes in terms of area. These classes represent important land cover categories associated with economic activities within the Protected Areas examined.

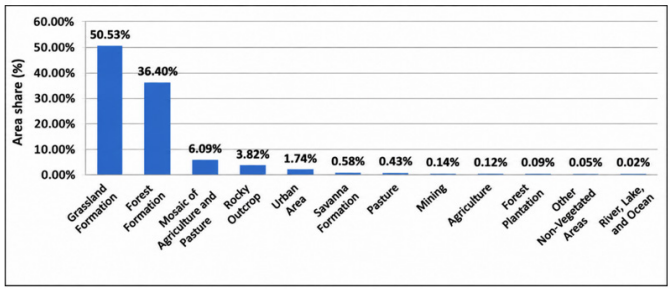

Figure 15 Percentage distribution of land use and land cover classes in municipally administered Strict Protection Areas within the Iron Quadrangle in 2020.

Source: Prepared by the authors (2026).

As further illustrated in Figure 15, forest, grassland, and savanna formations, rocky outcrops, surface water bodies (rivers, lakes, and oceans), and wetlands collectively accounted for 91.35% of the total area of municipally administered Strict Protection Areas. The predominance of these classes indicates that natural land cover remained the principal component of these Protected Areas, potentially contributing to biodiversity conservation.

Citation: Nero MA, Palhares AA. Spatiotemporal dynamics of land use and land cover in the iron quadrangle and its protected areas from 1985 to 2020. *MOJ Eco Environ Sci.* 2026;11(6):182–201. DOI: 10.15406/mojes.2026.11.00401

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The analysis of Table 5 and Figure 16 indicates that municipally administered Sustainable Use Areas experienced substantial changes in LULC over the 36-year study period. Among the classes associated with economic development, mining expanded by 400%, urban areas by 203%, and forest plantations by 128%. Among the land cover classes potentially associated with biodiversity conservation, savanna formations increased by 1%. Conversely, the most pronounced reductions were observed in agriculture (-84%) and surface water bodies, represented by the River, Lake, and Ocean class (-62%).

Table 5 Changes in land use and land cover in municipally administered Sustainable Use Areas over the 36-year period (1985–2020)

Class code	Hexadecimal	Color	Second-level LULC class	1985 (ha)	2020 (ha)	Change (ha)	Change (%)
3	006400		Forest Formation	28,477.70	26,968.89	-1,508.81	-5%
4	00ff00		Savanna Formation	694.08	699.78	5.70	+1%
9	ad4413		Forest Plantation	1,359.82	3,097.87	1,738.05	128%
11	45C2A5		Wetland	39.83	28.51	-11.32	-28%
12	B8AF4F		Grassland Formation	1,042.98	999.18	-43.80	-4%
15	FFD966		Pasture	11,773.99	10,795.22	-978.77	-8%
21	fff3bf		Mosaic of Agriculture and Pasture	6,129.71	6,348.37	218.66	+4%
24	aa0000		Urban Area	177.84	538.64	360.80	+203%
25	ff3d3d		Other Non-Vegetated Areas	277.09	212.38	-64.71	-23%
29	665a3a		Rocky Outcrop	57.02	65.12	8.10	+14%
30	af2a2a		Mining	216.18	1,081.65	865.47	400%
33	0000FF		River, Lake, and Ocean	794.24	299.23	-495.01	-62%
46	cca0d4		Coffee/Agriculture	111.98	17.60	-94.38	-84%

Source: Prepared by the authors (2026)

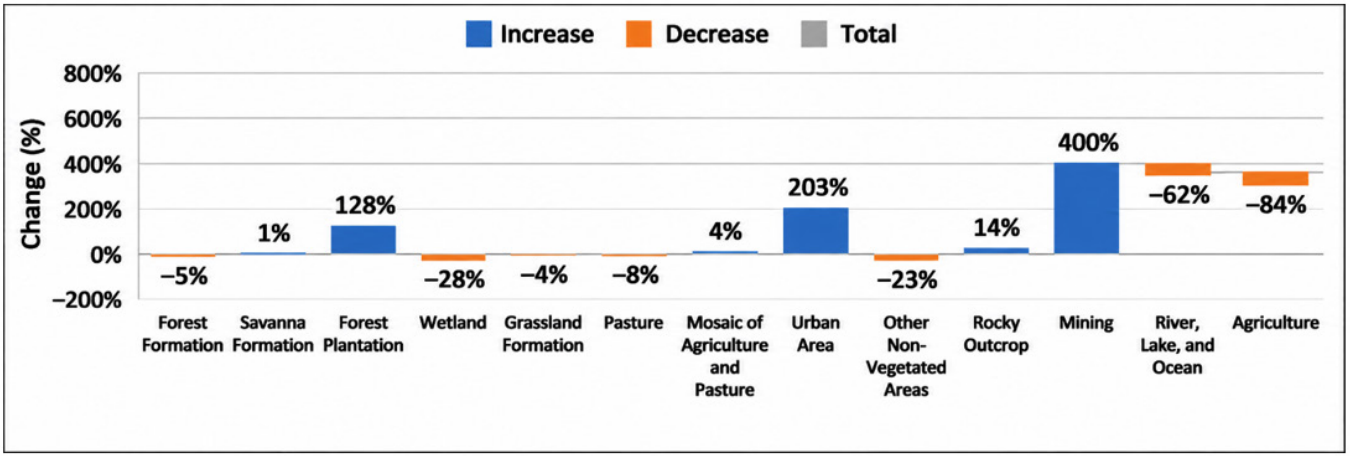

Figure 16 Percentage changes in land use and land cover classes in municipally administered Sustainable Use Areas within the Iron Quadrangle between 1985 and 2020.

Source: Prepared by the authors (2026).

As illustrated in Figure 17, despite the substantial expansion of economic activities, particularly mining (2.11%), urban areas (1.05%), and forest plantations (6.06%), these three LULC classes collectively accounted for 9.22% of the total mapped area of municipally administered Sustainable Use Areas in 2020. Forest plantations, mining, and urban areas ranked fourth, fifth, and eighth, respectively, among the mapped LULC classes in terms of area. These classes represent important land cover categories associated with economic activities within the Protected Areas examined.

Furthermore, Figure 17 shows that forest, grassland, and savanna formations, rocky outcrops, surface water bodies (rivers, lakes, and oceans), and wetlands collectively accounted for 56.81% of the total area of municipally administered Sustainable Use Areas. The predominance of these natural land cover classes indicates their potential contribution to biodiversity conservation, despite the expansion of anthropogenic activities.

Citation: Nero MA, Palhares AA. Spatiotemporal dynamics of land use and land cover in the iron quadrangle and its protected areas from 1985 to 2020. *MOJ Eco Environ Sci.* 2026;11(6):182–201. DOI: 10.15406/mojes.2026.11.00401

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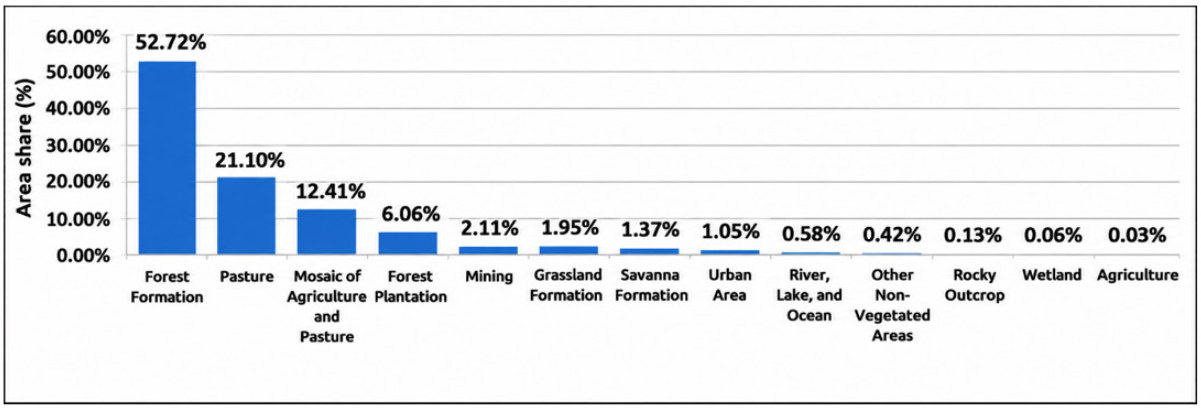

Figure 17 Percentage distribution of land use and land cover classes in municipally administered Sustainable Use Areas within the Iron Quadrangle in 2020.

Source: Prepared by the authors (2026).

The analysis of Table 6 and Figure 18 indicates that state-administered Strict Protection Areas experienced substantial changes in LULC over the 36-year study period (1985–2020). Among the classes associated with economic activities, mining expanded by 717%, forest plantations by 439%, and urban areas by 37%. Among the land cover classes potentially associated with biodiversity conservation, savanna formations increased by 3,324%, while grassland formations expanded by 14%. Conversely, the most pronounced reductions were observed in pasture (−79%), other non-vegetated areas (−65%), and surface water bodies, represented by the River, Lake, and Ocean class (−76%).

Table 6 Changes in land use and land cover in state-administered Strict Protection Areas over the 36-year period (1985–2020)

Class code	Hexadecimal	Color	Second-level LULC class	1985 (ha)	2020 (ha)	Change (ha)	Change (%)
3	006400		Forest Formation	12,670.12	12,245.20	-424.92	-3%
4	00ff00		Savanna Formation	3.55	121.56	118.01	+3,324%
9	ad4413		Forest Plantation	64.21	346.26	282.05	+439%
12	B8AF4F		Grassland Formation	8,767.36	9,975.70	1,208.34	+14%
15	FFD966		Pasture	899.85	186.93	-712.92	-79%
21	fff3bf		Mosaic of Agriculture and Pasture	1,884.90	1,160.57	-724.33	-38%
24	aa0000		Urban Area	86.85	118.92	32.07	+37%
25	ff3d3d		Other Non-Vegetated Areas	162.05	56.03	-106.02	-65%
29	665a3a		Rocky Outcrop	2,842.10	3,134.06	291.96	+10%
30	af2a2a		Mining	8.10	66.19	58.09	+717%
33	0000FF		River, Lake, and Ocean	34.05	8.10	-25.95	-76%
46	cca0d4		Coffee/Agriculture	58.01	61.65	3.64	+6%

Source: Prepared by the authors (2026).

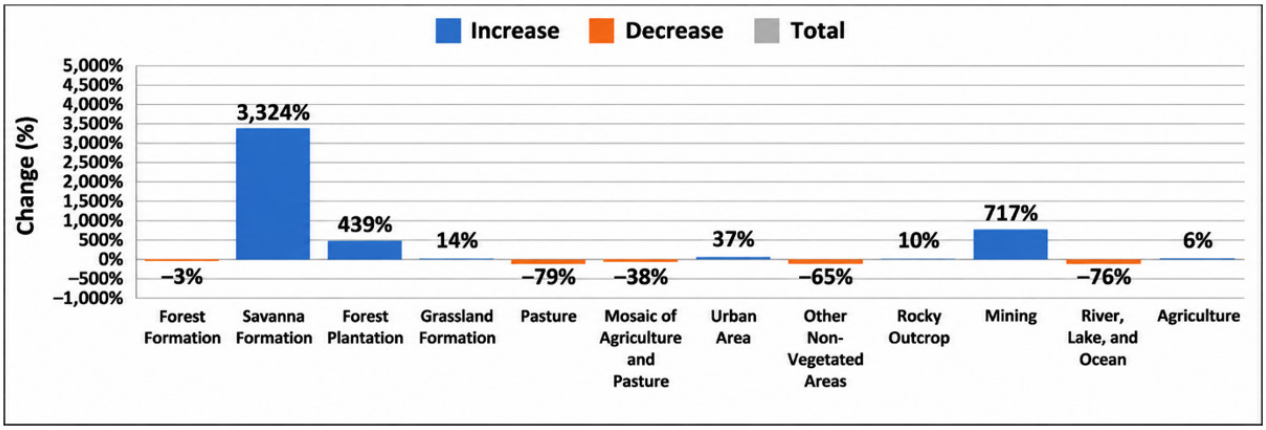

Figure 18 Percentage changes in land use and land cover classes in state-administered Strict Protection Areas within the Iron Quadrangle between 1985 and 2020.

Source: Prepared by the authors (2026).

Citation: Nero MA, Palhares AA. Spatiotemporal dynamics of land use and land cover in the iron quadrangle and its protected areas from 1985 to 2020. *MOJ Eco Environ Sci.* 2026;11(6):182–201. DOI: 10.15406/mojes.2026.11.00401

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As illustrated in Figure 18, despite the substantial expansion of land use and land cover (LULC) classes associated with economic activities, particularly mining (+717%) and forest plantations (+439%), as well as the expansion of urban areas, these three classes collectively accounted for only 1.93% of the total mapped area of state-administered Strict Protection Areas in 2020 (Figure 19). Forest plantations, urban areas, and mining ranked fifth (1.26%), eighth (0.43%), and ninth (0.24%), respectively, among the mapped LULC classes in terms of area. Together, these classes represent important categories associated with economic activities within the Protected Areas examined.

As further illustrated in Figure 19, forest formations (44.56%), grassland formations (36.30%), savanna formations (0.44%), rocky outcrops (11.40%), and surface water bodies (rivers, lakes, and oceans; 0.03%) collectively accounted for 92.73% of the total area of state-administered Strict Protection Areas. The predominance of these natural land cover classes suggests that a substantial proportion of these territories continues to support environmental conditions potentially favorable to biodiversity conservation.

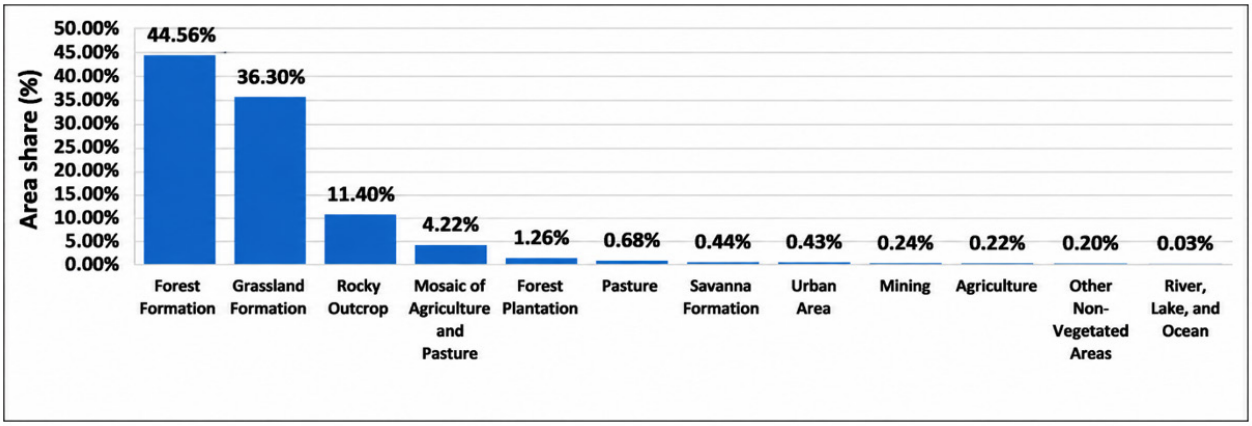

Figure 19 Percentage distribution of land use and land cover classes in state-administered Strict Protection Areas within the Iron Quadrangle in 2020.

Source: Prepared by the authors (2026).

The analysis of Table 7 and Figure 20 indicates that state-administered Sustainable Use Areas experienced substantial changes in LULC over the 36-year study period (1985–2020). Among the classes associated with economic activities, mining increased by 323%, forest plantations by 1,102%, and urban areas by 110%. Among the natural land cover classes potentially associated with biodiversity conservation, savanna formations exhibited an increase of 1,038%. Conversely, the most pronounced reductions were observed in agriculture (−73%), pasture (−31%), and surface water bodies, represented by the River, Lake, and Ocean class (−42%).

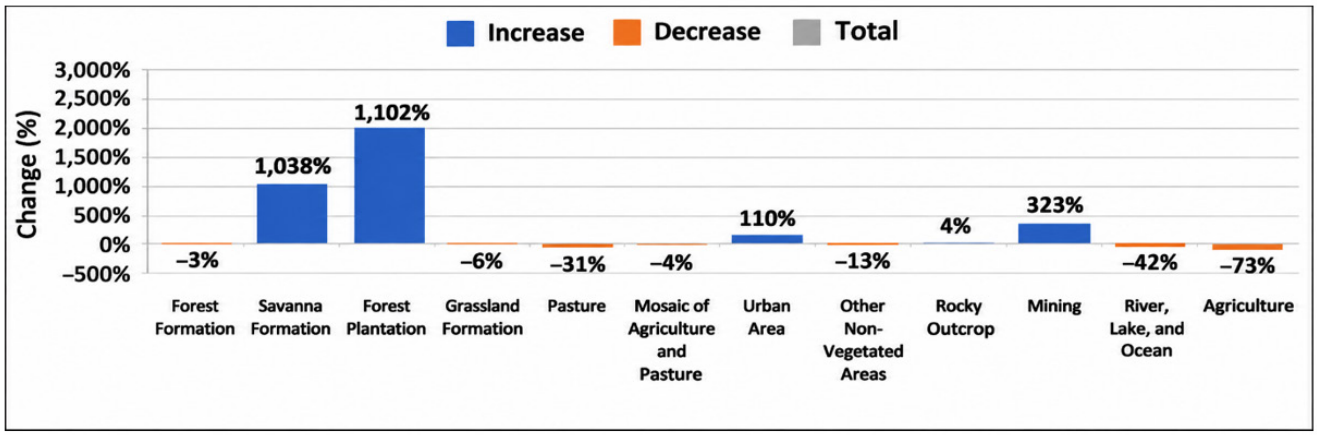

Figure 20 Percentage changes in land use and land cover classes in state-administered Sustainable Use Areas within the Iron Quadrangle between 1985 and 2020.

Source: Prepared by the authors (2026).

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Table 7 Changes in land use and land cover in state-administered Sustainable Use Areas over the 36-year period (1985–2020)

Class code	Hexadecimal	Color	Second-level LULC class	1985 (ha)	2020 (ha)	Change (ha)	Change (%)
0	-		Null / NoData	277,070.38	277,070.38	0.00	0%
3	006400		Forest Formation	89,328.34	87,028.18	-2,300.16	-3%
4	00ff00		Savanna Formation	79.25	902.16	822.91	+1038%
9	ad4413		Forest Plantation	194.78	2,341.39	2,146.61	+1102%
12	B8AF4F		Grassland Formation	52,225.50	49,305.31	-2,920.19	-6%
15	FFD966		Pasture	8,730.25	6,055.17	-2,675.08	-31%
21	fff3bf		Mosaic of Agriculture and Pasture	15,348.93	14,704.10	-644.83	-4%
24	aa0000		Urban Area	1,989.44	4,175.31	2,185.87	+110%
25	ff3d3d		Other Non-Vegetated Areas	1,141.15	990.83	-150.32	-13%
29	665a3a		Rocky Outcrop	11,001.24	11,417.00	415.76	+4%
30	af2a2a		Mining	1,274.28	5,391.41	4,117.13	+323%
33	0000FF		River, Lake, and Ocean	1,351.63	790.44	-561.19	-42%
46	cca0d4		Coffee/Agriculture	595.91	159.41	-436.50	-73%

Source: Prepared by the authors (2026).

Despite the substantial expansion of economic activities, particularly mining, urban development, and forest plantations, these three LULC classes collectively accounted for 6.50% of the total mapped area of state-administered Sustainable Use Areas in 2020, as illustrated in Figure 21. Mining, urban areas, and forest plantations ranked sixth, seventh, and eighth, respectively, among the mapped LULC classes in terms of area. Together, these categories represent important components of the anthropogenic land cover associated with economic activities in these Protected Areas. Furthermore, forest, grassland, and savanna formations, rocky outcrops, surface water bodies (rivers, lakes, and oceans), and wetlands collectively accounted for 81.55% of the total area of state-administered Sustainable Use Areas. This predominance of natural land cover suggests that these territories retain substantial areas potentially contributing to biodiversity conservation, despite the expansion of economic activities.

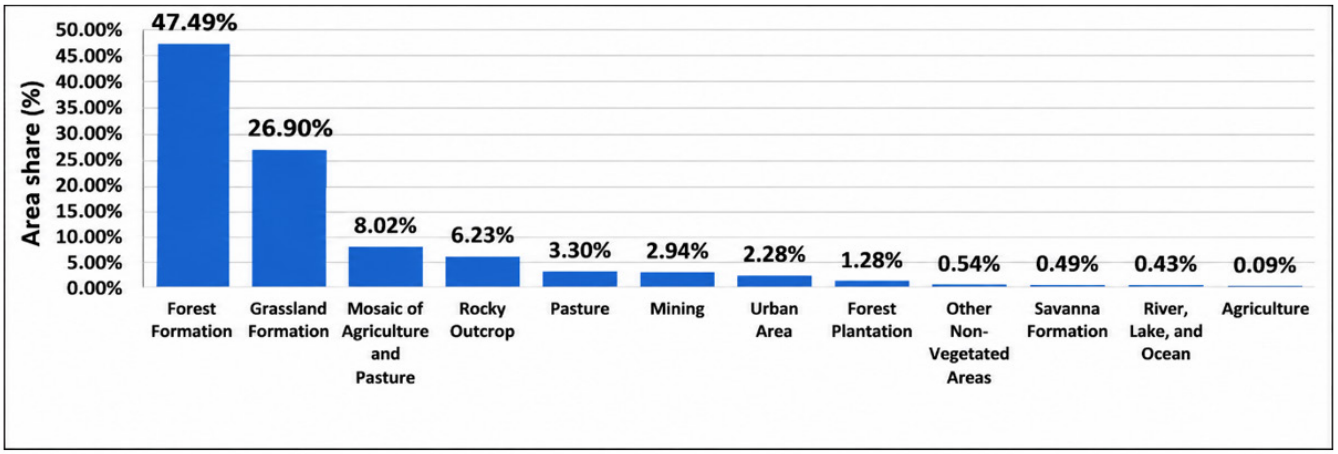

Figure 21 Percentage distribution of land use and land cover classes in state-administered Sustainable Use Areas within the Iron Quadrangle in 2020.

Source: Prepared by the authors (2026).

The analysis of Table 8 and Figure 22 indicates that the federally administered Strict Protection Area experienced substantial changes in land use and land cover (LULC) over the 36-year study period (1985–2020). Among the classes associated with economic activities, mining increased by 133%, while forest plantations exhibited a particularly pronounced relative increase of 27,613%. Among the natural land cover classes potentially associated with biodiversity conservation, savanna formations increased by 936%. Conversely, the most substantial reductions were observed in pasture (−64%), the mosaic of agriculture and pasture (−54%), and surface water bodies, represented by the River, Lake, and Ocean class (−56%).

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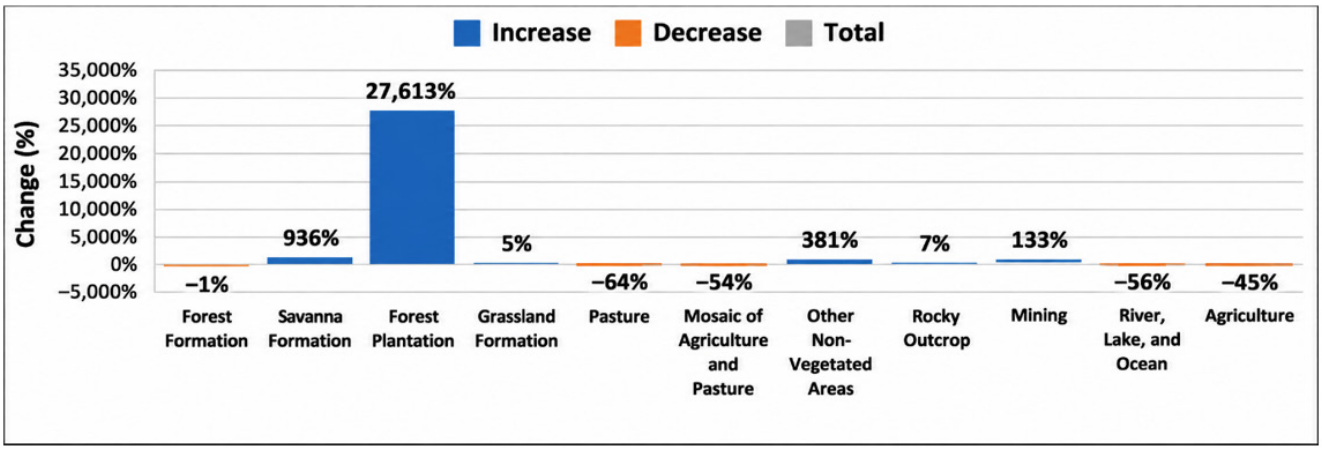

Figure 22 *Percentage changes in land use and land cover classes in the federally administered Strict Protection Area within the Iron Quadrangle between 1985 and 2020.*

Source: Prepared by the authors (2026).

Table 8 Changes in land use and land cover in the federally administered Strict Protection Area over the 36-year period (1985–2020)

Class code	Hexadecimal	Color	Second-level LULC class	1985 (ha)	2020 (ha)	Change (ha)	Change (%)
3	006400		Forest Formation	15,394.30	15,242.66	-151.64	-1%
4	00ff00		Savanna Formation	22.23	230.31	208.08	+936%
9	ad4413		Forest Plantation	1.16	320.64	319.48	27613%
12	B8AF4F		Grassland Formation	9,548.38	10,024.79	476.41	+5%
15	FFD966		Pasture	390.96	139.99	-250.97	-64%
21	fff3bf		Mosaic of Agriculture and Pasture	1,639.71	748.21	-891.50	-54%
25	ff3d3d		Other Non-Vegetated Areas	5.95	28.59	22.64	+381%
29	665a3a		Rocky Outcrop	4,178.12	4,478.42	300.31	+7%
30	af2a2a		Mining	2.23	5.21	2.98	+133%
33	0000FF		River, Lake, and Ocean	2.64	1.16	-1.48	-56%
46	cca0d4		Coffee/Agriculture	76.36	42.06	-34.30	-45%

Source: Prepared by the authors (2026).

As illustrated in Figure 23, despite the substantial relative expansion of forest plantations and mining activities, these two LULC classes collectively accounted for only 1.05% of the total mapped area of the federally administered Strict Protection Area in 2020. Forest plantations and mining ranked fifth and tenth, respectively, among the mapped LULC classes in terms of area. Although these classes represent land cover categories associated with economic activities, their combined spatial extent remained relatively limited compared with the predominant natural land cover classes.

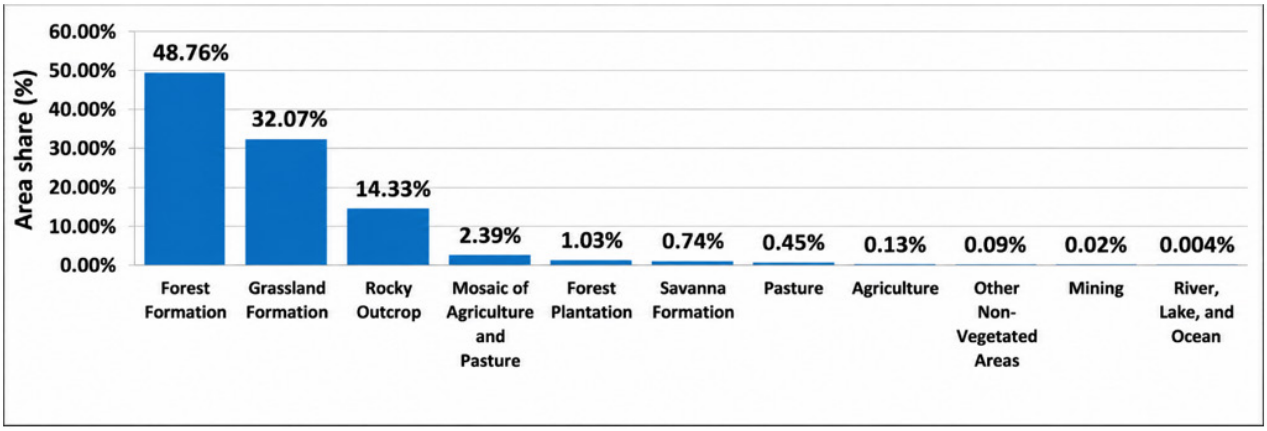

Figure 23 *Percentage distribution of land use and land cover classes in the federally administered Strict Protection Area within the Iron Quadrangle in 2020.*

Source: Prepared by the authors (2026).

Citation: Nero MA, Palhares AA. Spatiotemporal dynamics of land use and land cover in the iron quadrangle and its protected areas from 1985 to 2020. *MOJ Eco Environ Sci.* 2026;11(6):182–201. DOI: 10.15406/mojes.2026.11.00401

Furthermore, forest, grassland, and savanna formations, rocky outcrops, surface water bodies (rivers, lakes, and oceans), and wetlands collectively accounted for 95.89% of the total area of the federally administered Strict Protection Area. The predominance of these classes indicates that natural land cover remained the principal component of the Protected Area in 2020, potentially contributing to biodiversity conservation.

Conclusion

This study revealed substantial changes in land use and land cover (LULC) over the 36-year period from 1985 to 2020, both within the Iron Quadrangle (IQ) and across the Protected Areas (PAs) examined. Nevertheless, the findings indicate a certain degree of balance between land use transformations and the persistence of natural land cover. As expected, mining, forestry plantations, and urban areas were among the LULC classes exhibiting the greatest expansion, with increases observed across all analytical scenarios. Despite these changes, these three classes collectively accounted for 11.76% of the mapped area of the Iron Quadrangle in 2020, the final year of the assessment. In contrast, land cover classes associated with biodiversity conservation, including forest, savanna, and grassland formations, rocky outcrops, wetlands, and surface water bodies (rivers, lakes, and oceans), collectively represented 62.71% of the study area. These findings indicate that natural land cover remained predominant in the Iron Quadrangle at the end of the study period.

Despite the region's intensive economic development and the expansion of anthropogenic activities over the past 36 years, the results suggest that areas associated with biodiversity conservation continued to occupy a substantially greater proportion of the Iron Quadrangle than the land cover classes directly associated with mining, forestry plantations, and urbanization. The Protected Areas located within the region contributed to this pattern, particularly those classified under the Strict Protection group, where land use restrictions are generally more stringent than those established for Sustainable Use areas.

Increases in mining, forestry plantations, and urban areas were observed across all groups of Protected Areas evaluated. Nevertheless, land cover classes associated with biodiversity conservation occupied considerably larger proportions of their respective territories. Within municipally administered Strict Protection Areas, the combined extent of the three expanding anthropogenic classes accounted for 1.97% of the total area, whereas classes associated with biodiversity conservation represented 91.35%. In municipally administered Sustainable Use Areas, the proportion associated with biodiversity conservation was lower, reaching 56.81%, while the three anthropogenic classes accounted for 9.22%. At the state administrative level, the corresponding proportions of anthropogenic land cover were 1.93% in Strict Protection Areas and 6.50% in Sustainable Use Areas, whereas conservation-associated classes represented 92.73% and 81.55%, respectively. In federally administered Strict Protection Areas, the three anthropogenic classes accounted for only 1.04% of the total area, while conservation-associated land cover reached 95.89%.

These findings indicate that Sustainable Use Areas and municipally administered Protected Areas exhibit comparatively greater vulnerability to land use transformations associated with economic activities. Nevertheless, natural land cover remains predominant in these territories, suggesting that biodiversity conservation and economic activities continue to coexist, although with varying degrees of anthropogenic pressure depending on the protection group and administrative jurisdiction.

Despite the relatively high proportions of land cover associated with biodiversity conservation, one particularly concerning finding was the reduction in the surface water class (rivers, lakes, and oceans) across all scenarios evaluated. This pattern deserves particular attention because a sustained decline in mapped surface water extent may indicate increasing pressure on regional water resources and potential risks to water availability. Further investigations are therefore necessary to determine the underlying causes of these changes and assess their implications for regional water security.

The methodological approach proved effective for assessing LULC dynamics and identifying patterns relevant to biodiversity conservation, demonstrating its potential applicability to other Protected Areas throughout Minas Gerais State. Nevertheless, further methodological refinements are recommended. In the present study, 1985, the first year covered by MapBiomas Collection 6, was adopted as the common baseline for all Protected Areas, regardless of their official establishment dates. However, some Protected Areas were established during the 1970s, whereas others were designated after 2000. Future assessments should therefore consider the official establishment date of each Protected Area when defining the temporal baseline for evaluating LULC changes. Although the adoption of a common baseline did not alter the mapped land cover conditions or the area calculations, incorporating the establishment dates would allow a more accurate interpretation of changes occurring before and after legal protection and provide a more refined assessment of conservation outcomes and anthropogenic pressures.

An important methodological contribution of this research was the application of freely available geospatial datasets and open-source tools, particularly QGIS, together with R-based programming and analytical algorithms. This approach demonstrates the feasibility of conducting multitemporal LULC assessments without relying on proprietary geospatial software or costly satellite imagery. Future research could expand this framework by incorporating satellite products with improved spatial and temporal resolution, including imagery from the Brazilian Amazonia-1 satellite and, subject to data-access conditions, Planet satellite products. More recent MapBiomas collections could also be incorporated to extend the monitoring period, improve thematic consistency, and support continued assessments of land use dynamics and biodiversity conservation in the Iron Quadrangle and its Protected Areas.

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Conflicts of interest

There is no conflict of interest.

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