

Structural intelligence and strategies for environmental conservation in Brazil: a case study of Serra do Gandarela National Park

Abstract

The Serra do Gandarela National Park, a Fully Protected Area established in Brazil by Law No. 9,985 of July 18, 2014,¹⁵ faces increasing anthropogenic pressures that threaten its biodiversity. This research uses structural intelligence techniques through the use of Landscape Ecology metrics, including the Fragstats^{30 software} and Mapbiomas data²⁹, to diagnose these pressures and suggest sustainable alternatives, such as ecotourism. The objectives of this work were to diagnose, through Landscape Ecology metrics and tools, the anthropogenic pressures that the Serra do Gandarela National Park has suffered in relation to its biodiversity, to propose solutions and stimulate studies for the scientific community on the pressures identified from the engagement of stakeholders, namely: the Public Prosecutor's Office of the State of Minas Gerais, the government of the State of Minas Gerais, society in general, among others. The aim is to support the academic community, government officials, other stakeholders and society in general in carrying out studies on the potential for ecotourism in the park's surroundings and for community-based tourism as an alternative to mineral exploration. Tools such as Fragstats (version 4.2)³⁰, maps and information from Mapbiomas²⁹ were used for the methodology. Guidelines from the Stakeholder Engagement Handbook (BiodivERSA, 2014)³¹ were also used to identify and categorize stakeholders. It was concluded that the study area is undergoing an ongoing process of anthropization with a significant increase in anthropized areas, especially urbanized and mined areas. Thus, this conclusion is of great importance in guiding public policies and engaging society and managers in community tourism and conservation practices.

Keywords: serra do gandarela national park, diagnosis, stakeholders, metrics

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Abbreviations: CU, Conservation Unit; NSCU, National System of Conservation Units; NP, National Park; SGNP, Serra do Gandarela National Park; PPOSMG, Public Prosecutor's Office of the State of Minas Gerais; CAA, Conduct Adjustment Agreement; UN, United Nations; SDGs, Sustainable Development Goals; QGIS, Quantum GIS; SHAPE_MN, Mean Shape Index; FRAC_MN, Mean Fractal Index; TCA, Total Core Area of the Class; CORE_MN, Mean Core Area; NDCA, Number of Disjoint Core Areas

Introduction

The contemporary global scenario, marked by the intensification of pressure on natural resources and their related environmental impacts, imposes the urgent need for strategies that reconcile environmental preservation with sustainable socioeconomic development.¹⁻¹⁰ In this context, national parks, as a category of Conservation Unit (CU), emerge as one of the predominant approaches adopted internationally for the protection of ecosystems.¹¹⁻¹⁴

The National System of Conservation Units (NSCU), established by Brazilian legislation, classifies the National Park (NP) as a fully protected unit, intended for the preservation of natural ecosystems of significant ecological and aesthetic relevance, enabling scientific research, educational activities, recreation in natural environments and ecological tourism.¹⁵ Therefore, the park in question represents a management model that integrates environmental conservation with sustainable uses, in contrast to other categories of CU's that restrict public access in more rigorous ways.

In this sense, the Serra do Gandarela National Park (SGNP) is a NP, created in 2014 and located in the State of Minas Gerais, Brazil, approximately 40 km from the capital, Belo Horizonte, covering an area of 31,270 hectares. It is located in the region known as Iron Quadrangle and in the southern portion of the Serra do Espinhaço.¹⁶ The park is a territory of high relevance for environmental conservation, given its role in the preservation of unique ecosystems and robust biodiversity, composed of rivers, waterfalls, rocky fields and a rich fauna and flora, with high ecotourism potential.¹⁷

However, the creation of the park was marked by controversy due to pressure from the mining industry, whose interests often conflict with the demands of the local community regarding environmental conservation.¹⁸

Despite its recent creation, the park already faces challenges related to the infrastructure needed to meet a growing demand for ecological and community-based tourism, which could represent a sustainable alternative to mining activities.¹⁶ The presence of ferruginous rocky fields and aquifers that supply Belo Horizonte and neighboring municipalities makes SGNP a target for mining interests, mainly due to the potential for exploiting canga, a rare ferruginous geosystem.¹⁹

The Public Prosecutor's Office of the State of Minas Gerais (PPOSMG) plays an essential role in protecting the park, with actions such as the signing of a Conduct Adjustment Agreement (CAA) with the municipality of Caeté, which aims to preserve a local paleoburrow, an important record of the region's extinct megafauna.²⁰

The SGNP is a space of contrasts. On the one hand, it is a reserve of unique biodiversity and hydrological and mineral wealth. On the other, it is a territory with great mining potential that attracts constant investment from the extractive sector. In this context, it is essential to systematically assess land cover and use in the park and its surroundings, seeking to provide support for public policies aimed at environmental conservation and sustainable development.

Landscape Ecology emerges as an appropriate scientific tool for this analysis, as it allows us to understand the dynamics of land use and occupation, as well as anthropogenic interactions with the landscape.^{21,22} According to the European Landscape Convention, the landscape encompasses both natural and anthropogenic factors, and is a unit of analysis that combines environmental, social and cultural aspects.²² This branch of knowledge uses metrics and assessment techniques to diagnose environmental impacts, support planning scenarios and promote the sustainable integration of different land uses.²²

Given these considerations, this research comprehensively assesses the anthropogenic pressures on biodiversity and geodiversity in the SGNP, applying structural intelligence techniques through the use of Landscape Ecology metrics and dynamic land use and occupation analysis techniques. The study also seeks to develop mitigation and adaptation guidelines that are based on the strategic engagement of different stakeholders to promote sustainable environmental management in the park’s area of influence. Through this methodology, we intend to provide relevant scientific and methodological support to the academic community, as well as to public managers and various social actors, with a view to guiding new research and policies aimed at low-impact ecotourism and community-based tourism, considering it as a sustainable economic alternative as opposed to mining exploration activities.^{23–28}

In the specific context of the SGNP, the technical and scientific literature points to a scenario of landscape transition, with continuous expansion of urbanized and mined areas. However, comprehensive studies that integrate both details from Landscape Ecology studies and stakeholder analysis to diagnose these pressures are still limited. Thus, this work seeks to fill this gap by proposing an integrated approach to diagnose the dynamics of land use and land cover and identify important anthropogenic pressures. The application of tools such as Fragstats³⁰ and Mapbiomas,²⁹ combined with strategic *stakeholder engagement*, makes the study replicable for other similar areas both in Brazil and worldwide.

The specific objectives of this study are the detailed quantification of land use and land cover classes in the SGNP, using advanced metrics of Landscape Ecology. The aforementioned mapping aims to diagnose environmental pressures more accurately, identifying areas of high ecological sensitivity. Another specific objective is to map and analyze the interests of stakeholders involved in the conflict between mining and conservation. Through the use of participatory methodological procedures and strategic engagement, the aim is to facilitate dialogue between the different actors, promoting the identification of sustainable alternatives for regional development. Thus, a set of alternatives and scenarios for the integrated management of the area will be proposed, based on scientific evidence, aimed at preserving ecosystem services and promoting ecotourism as a viable strategy for conservation and sustainable development.

Based on the data and analyses obtained, a set of alternatives and scenarios will be proposed for the integrated management of the area, based on scientific evidence, aimed at preserving ecosystem services and promoting ecotourism as a viable strategy for conservation and sustainable development.

Table 1 Landscape metrics used

Group	Metric	Observation	Type
Area	CA/TA - Total Area	Total area of each class	Structural
	PLAND	Percentage of class in the landscape	Structural
Edge	TE - Total edge	Total area of the edges of the spots of all classes	Structural
	SHAPE_MN - Mean shape index	Average shape index of patches in each class (lower limit = 0 if regular and no upper limit)	Structural
Shape	SHAPE_SD - Standard deviation shape index	Standard deviation of the mean shape index of the spots of each class	Structural
	FRAC_MN - Mean fractal dimension	Average fractal dimension index of the spots in each class (greater than 0; equal to 1 if the spots are regular; and equal to 2 if irregular)	Structural
	FRAC_SD - Standard deviation fractal dimension	Standard deviation of the mean fractal dimension index of the spots in each class	Structural
Core	TCA - Total core area	Total area of the spot cores of each class	Structural
	CPLAND - Core area percentage of landscape	Percentage of the core area of each class in relation to the landscape	Structural
	NDCA - Number of disjunct core areas	Number of disjoint core areas per class	Functional
	CORE_MN - Mean Core Area	Average core area of spots in each class	Structural
	CORE_SD - Standard deviation of the Core Area	Standard deviation of the mean core area of the spots of each class	Structural
Aggregation	ENN_MN - Mean euclidean nearest neighbor distance	Average Euclidean distance to the nearest neighbor of the patches of each class	Functional
	ENN_SD - Standard deviation of the mean euclidean nearest neighbor distance	Standard deviation of the mean Euclidean distance to the nearest neighbor of the patches of each class	Functional
	NP - Number of patches	Number of spots of each class	Structural

Source: From the authors

The park under study is important for biodiversity conservation, as documented by authors in the technical-scientific literature.¹⁶⁻¹⁹ Therefore, considering compliance with the United Nations (UN) 2030 Agenda,^{23,24} this work is aligned with the following Sustainable Development Goals (SDGs): SDG 6 (Clean Water and Sanitation), SDG 8 (Decent Work and Economic Growth), SDG 12 (Responsible Consumption and Production), and SDG 15 (Life on Land). Since it preserves ecosystems and important aquifers that supply the metropolitan region of the capital of Minas Gerais, Belo Horizonte, it offers alternatives for the development of sustainable tourism, which supports SDG 8 (Decent Work and Economic Growth) and SDG 12 (Responsible Consumption and Production). By studying anthropogenic pressures and proposing guidelines for ecotourism that favor environmental conservation and economic development, this work also contributes to the climate agenda (SDG 13), promoting a sustainable management model for areas of high environmental and economic relevance.

Materials and methods

To answer the questions proposed in this study, a methodology based on structural intelligence techniques was adopted through the use of Landscape Ecology metrics applied to spatial matrix data. The study area covers the polygon of the Serra do Gandarela National Park, including a buffer zone of 3 km radius around the perimeter of the park. Land cover and use were obtained from the MapBiomias project database,²⁹ covering the years 2000 (prior to the creation of the park), 2010 (period close to the creation proposal) and 2021 (most recent collection). These matrix data were delimited for the area of interest using the Quantum GIS (QGIS) software (version 3.16.16).²⁵ Using the Fragstats software (version 4.2),³⁰ landscape metrics were calculated, considering an edge depth of 100 meters, a connectivity rule of 8 neighboring cells and no sampling strategy. Land use and land cover maps, as well as the *rasters* used, are documented in the results and discussions section.

In quantitative landscape analysis, the concepts of composition and configuration are fundamental and intrinsically interconnected. Composition encompasses the constituent elements of the landscape and their quantification, while configuration deals with the spatial arrangement of the components, that is, the structural disposition of the elements in space.²¹ These concepts support the study of fragmentation, defined as the reduction of vegetation cover until it is restricted to isolated forest fragments, with variations in size and spatial shape and limited to a finite set.²²

Several metrics have been developed to quantify the composition and configuration of these fragments, with a focus on structural and functional metrics. Structural metrics provide a chorological and horizontal description of the fragments, addressing the morphology and spatial distribution of the elements without considering ecological aspects. In contrast, functional metrics incorporate ecological attributes when examining the fragments, adopting a topological and vertical approach to analyze the organization of the landscape elements.

The phenomenon known as edge effect describes the pressure that an anthropized matrix exerts on adjacent forest fragments. Thus, the configuration of the patches, especially the shape of the fragments, plays an important role in their resistance to the pressures imposed by the matrix. Fragments with rounded shapes have a larger core area, which increases their resilience to the edge effect. In contrast, fragments with reduced core areas are more susceptible to external pressures. From an ecological point of view, edge areas favor the

development of pioneer species due to less competition for sunlight, which alters the balance of the plant community.²¹

Based on this rationale, specific metrics were selected, organized in Table 1, and classified according to their type, whether functional or structural. All metrics were calculated at the class level, allowing a detailed and ecologically relevant analysis of the landscape under study.

The process of identifying stakeholders began with the application of the ex-ante method, following the guidelines of the Stakeholder Engagement Handbook (BiodivERSA, 2014).³¹ A preliminary stakeholder analysis was used, which involved a literature review and consultation of institutional documents and environmental reports relevant to the study area. Data were collected from multiple sources to ensure a broader view of the stakeholders involved. This procedure included searching for government documents from the state of Minas Gerais, prioritizing those that contained information about the SGNP and Brazilian environmental legislation involving information related to parks and conservation units.

Initially, in phase 1, “Who are your stakeholders?”, the ex-ante method was adopted for preliminary identification of interest groups using previously established categories. These categories were based on a stakeholder analysis of the park ecosystem, as proposed by.²⁶ Stakeholders were classified into public sector, private sector and third sector, with the addition of a fourth group – contiguous populations – considering the presence of villages, settlements and rural communities and areas investigated.

Stakeholders were then organized according to phase 2, which examines the influence and interest of each group in the context of the research. This step involved a detailed assessment of each group to allow for a contextual analysis of each stakeholder’s potential impact.

Finally, phase 3, “Understand your stakeholders”, delved deeper into the survey and analysis of interpersonal and institutional relationships between identified groups, examining the activities, level of knowledge and engagement of each stakeholder in relation to the project. This last stage was based on defining communication strategies and identifying possible challenges in engagement, in order to align the objectives of the study with the reality of the stakeholders involved.

These tools and methods integrate spatial data and qualitative analyses, directly aligning with the study objectives and ensuring a robust and multidimensional approach. This innovative methodology reinforces the scientific and practical applicability of the study, offering replicable guidelines for the management of protected areas in contexts of anthropogenic pressure. A flowchart containing the methodological procedures of this work is found in Figure 1, below.

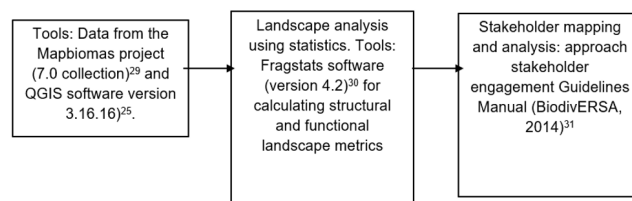


Figure 1 Flowchart of methodological procedures. Source: The authors (2024).

Results and discussions

The analysis of land use and occupation in the study area and its buffer zone allowed the identification of patterns and trends of

transformation throughout the periods evaluated, namely 2000, 2010 and 2021. Through the maps generated, it was possible to visualize the dynamics of expansion of anthropic areas, such as urbanization and mining, in contrast with the reduction of plant and natural formations, especially fragments of the Atlantic Forest and rocky fields.

The results, observed in the maps shown in Figures 2–4 below, reflect a process of anthropization, highlighting not only the loss of biodiversity, but also the fragmentation of habitats and the consequent ecological vulnerability of the region.

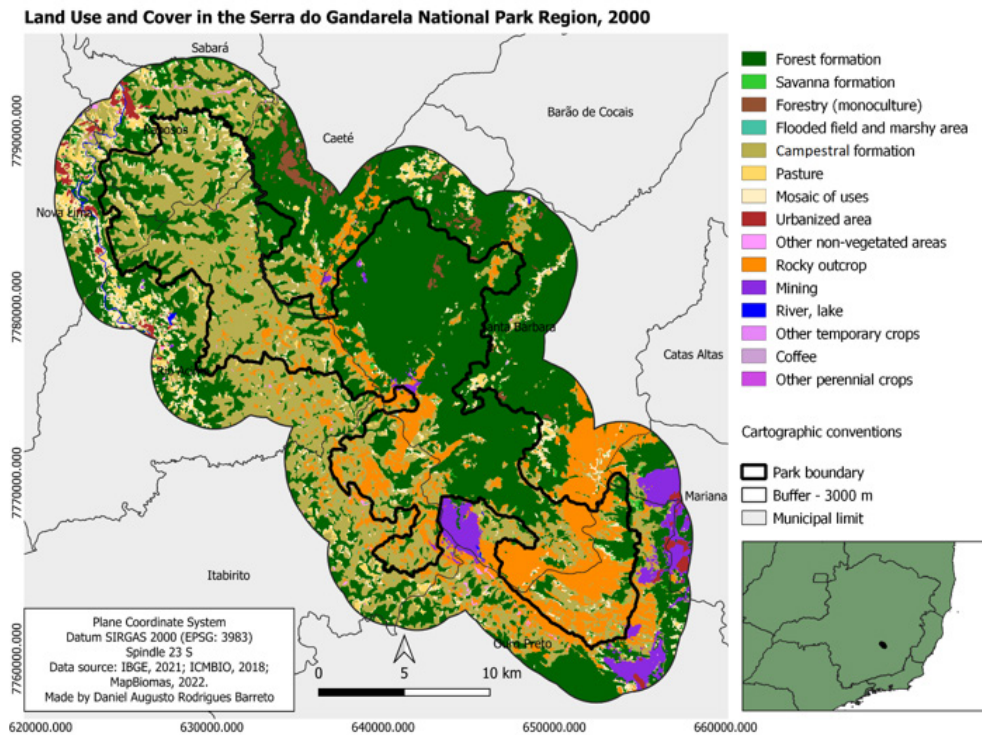


Figure 2 Land Use and Cover in the SGNP region in different periods. Source: The authors (2024).

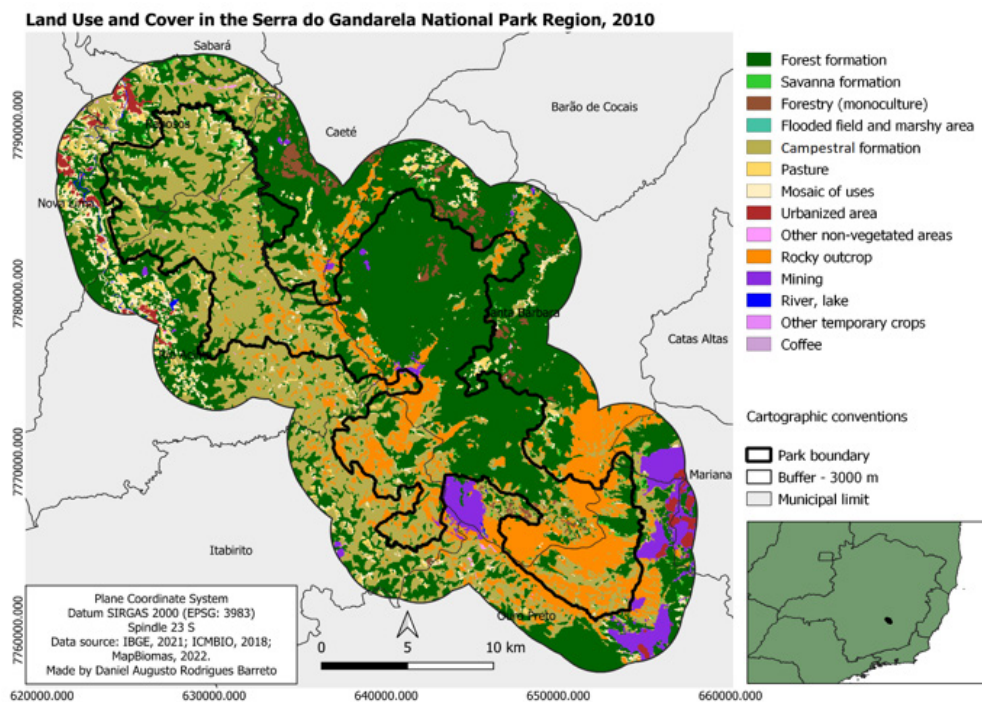


Figure 3 Land Use and Cover in the SGNP region in different periods. Source: The authors (2024).

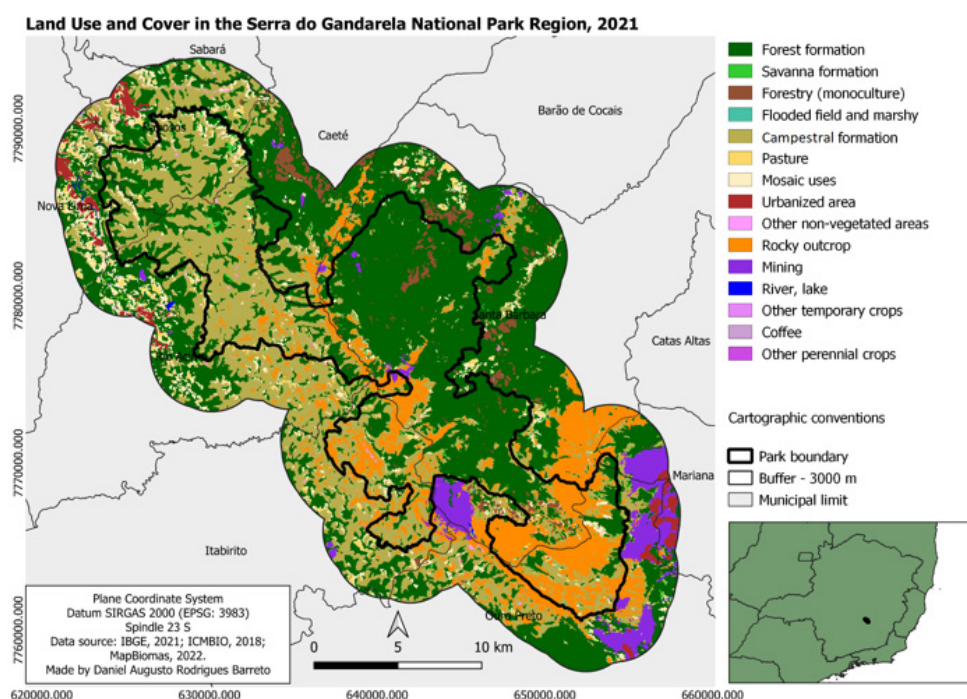


Figure 4 Land Use and Cover in the SGNP region in different periods. Source: The authors (2024).

By calculating the metrics for the years analyzed, the Tables 2–5 were generated in sequence.

Table 2 Landscape metrics for the year 2000

Source: The authors (2024)

Table 3 Landscape metrics for the year 2010

Source: The authors (2024)

Table 4 Landscape metrics for the year 2021

Source: The authors (2024)

Table 5 Landscape metrics for variation

Source: The authors (2024)

To minimize biases in the time frame, the 2010 data were adjusted, ensuring consistency in the longitudinal analysis. However, a progressive increase was observed between the three periods analyzed in anthropogenic classes, notably in the categories of Urbanized Area, Forestry (monoculture), and Mining, as inferred by visual analysis. The variation recorded between 2000 and 2021 shows that the class most affected by the loss of area was pasture, whose distribution is predominantly concentrated in the west-northwest quadrant. This decline is related to the expansion of urban areas in the municipalities of Nova Lima, Raposos, and Rio Acima. In contrast, the forestry and mining classes showed significant growth, with mining being particularly prominent in the southwest region, with significant expansion in the areas of Ouro Preto and Mariana, cities close to Belo Horizonte, an important metropolitan region, in the state of Minas Gerais, Brazil.

Regarding the susceptibility to forest fires in SGNP, a predictive model revealed a higher risk in the northwestern portion of the park. This pattern was corroborated by a prolonged fire recorded in the last dry season near Nova Lima, suggesting a possible correlation

between urban expansion and vulnerability to fire. Previous studies on forest fires based on data indicate that savanna vegetation and rocky fields are more susceptible to fires due to their limited water retention capacity, a characteristic intensified during the dry season, particularly in August, the month in which the aforementioned fire occurred.³²

Additionally, the study area located between the cities of Caeté and Santa Bárbara, both located in the State of Minas Gerais, and around SGNP, is home to the ongoing environmental licensing process for the Apolo Project of the mining company Vale SA, as illustrated in Figure 5 below.

The area claimed by the mining company Vale SA was part of the negotiations for the delimitation of the Serra do Gandarela National Park and is subject to a vegetation suppression plan that aims to explore the canga areas (rocky outcrop land class) of the Gandarela syncline for up to 29 years, according to documents from the aforementioned mining company.

Considering the anthropogenic pressures on the park area, it is plausible to assume that the removal of vegetation in this area will increase the demand for forestry studies. In the Environmental Impact Report, the Apolo Project anticipates a scenario in which the landscape, currently dominated by native vegetation, will give way to anthropogenic areas marked by the presence of pits, plants and piles of sterile material, mainly in places currently occupied by forests and rocky fields. With the execution of the project, a reduction in the total area of forest formation was observed, which includes fragments of the Atlantic Forest – notably the Montana semideciduous seasonal forest (forest formation land class). The Total Class Edge Area (TE) metric for this class increased, indicating greater fragmentation, accompanied by increases in the Mean Shape Index (SHAPE_MN) and Mean Fractal Index (FRAC_MN), which suggest more irregular shapes of forest patches.

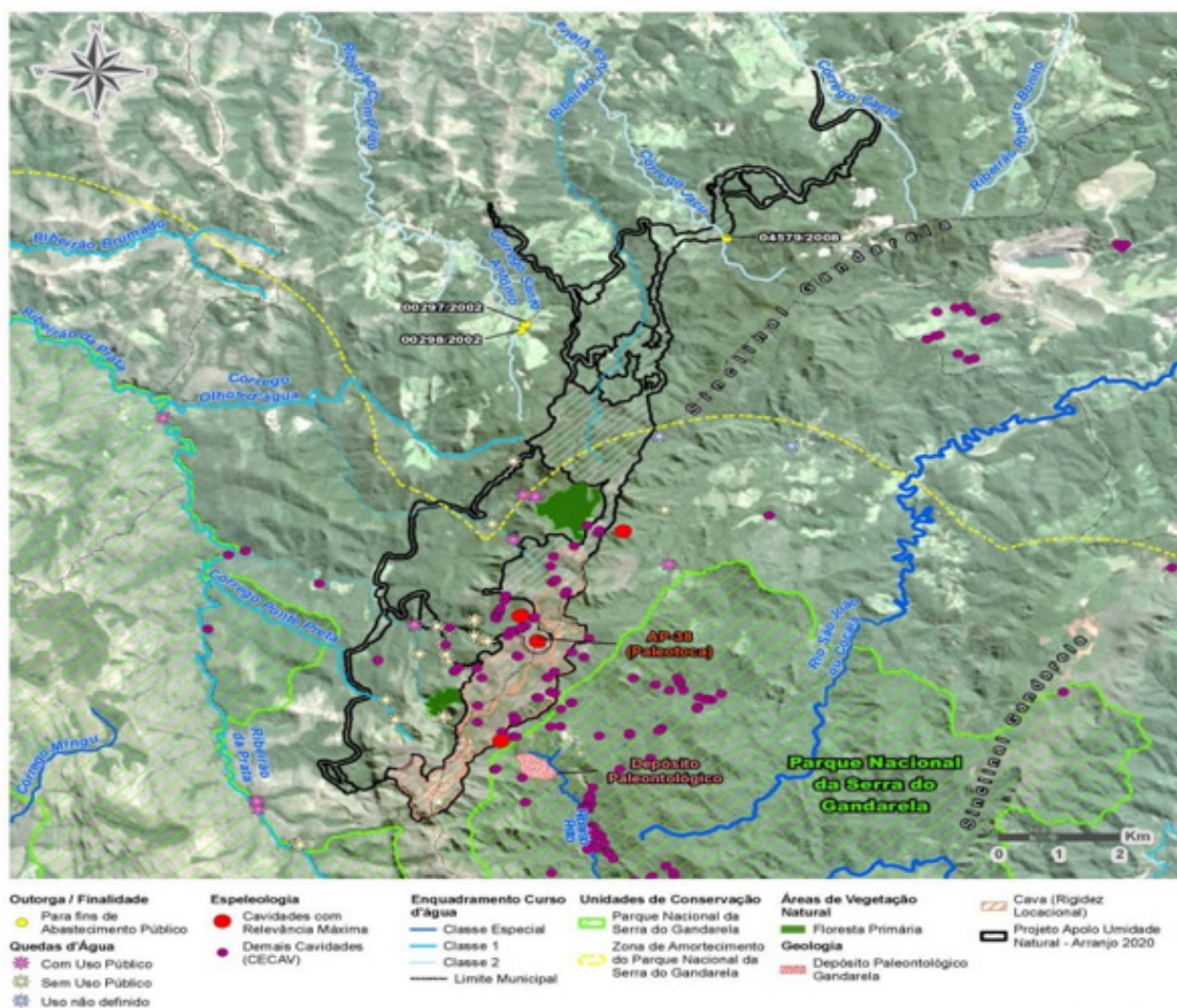


Figure 5 Relevant Environmental Attributes - RIMA Apolo Project. Source:VALE;Amplio, 2021.³³

These characteristics imply greater susceptibility to the edge effect. In addition, there was a significant loss of the Total Core Area of the Class (TCA), a reduction in the Mean Core Area (CORE_MN) and an increase in the Number of Disjoint Core Areas (NDCA), factors that reflect the degradation of the remaining forest fragments. A decrease in the average aggregation metric of Euclidean distance was also observed, indicating a greater proximity between forest fragments, possibly increasing the contiguity between them due to fragmentation.

Other vegetation classes, such as campestrial formation and rocky outcrops (non-forest), also presented similar dynamics. However, the savanna formation class exhibits a peculiarity due to its proximity to campestrial formation, which suggests potential inaccuracy in the classification method.

The general trend indicates a gradual and consistent replacement of natural features by anthropogenic ones, with classes such as urban areas and mining showing continuous expansion and prolonged uses, with no immediate prospects for forest regeneration.

Table 6 summarizes the identification of the stakeholders involved, categorizing them into public sector, private sector, third sector and general public, and specifying the reasons for their involvement, as

well as the benefits of this participation.

The conservation of the SGNP requires, above all, an integrated management approach, based on the collaboration of various sectors involved, as well as on the strategic alignment of the interests of stakeholders. To achieve this goal, it is very important to implement participatory forums that bring together NGOs in their joint effort to mitigate anthropogenic pressures and promote more sustainable practices. The use of advanced technologies, such as remote monitoring systems and spatial data analysis, is essential for identifying critical environmental pressures and for strategic planning of mitigation actions. In addition, financial mechanisms, such as environmental compensation funds and tax incentives, must be established to ensure that conservation costs are distributed equally and equitably among the stakeholders involved. Finally, strengthening community-based tourism is a viable economic alternative, because it not only promotes the engagement of local populations, but also ensures the maintenance of ecosystem services that are important for the maintenance of life. Thus, these strategies, supported by scientific evidence and collaborative dialogue, are essential to reconcile regional economic development with environmental preservation in areas of high ecological relevance, such as the SGNP.³³

Table 6 Stakeholder identification and categorization matrix

Stakeholder	Category (Public sector, private sector, third sector, general public)	Reasons to involve the stakeholder	Why would the stakeholder like to be involved (benefits)?
Ecotourist	General public	Directly interested in ecotourism practices in the region, both as planners/service providers and as practitioners	Economic return, enjoy the scenery
ICMBIO	Public sector	Responsible for the administration and management of Parna Gandarela, federal UC.	Biodiversity conservation
Mining companies	Private sector	Some companies have projects close to the study area	Economic exploitation of mineral wealth in the region
SISEMA	Public sector	Responsible for coordinating environmental policy in the state	Environmental management and enforcement of legislation
Surrounding towns/villages	General public	Residence near the park	Economic use of the area (production of candeia, moss, family farming, etc.)
Producers on private property/ community land	General public	Since the demand for the creation of the park, they have been waiting for the creation of a Sustainable Development Reserve	The region may have new CUs created, and its Buffer Zone is currently being developed.
Government of Minas Gerais	Public sector	State interest in public domain assets	Area of public domain, as environmental and historical heritage. Collection and generation of employment.
Municipalities	Public sector	The park area encompasses several municipalities, with different economic perspectives. Some, like Rio Acima, are against mining operations, while others, like Caeté, want to obtain financial compensation for mineral exploration.	Generate returns on revenue collection
NGO Gandarela Waters	Third sector	Movement that actively participated in the request for the creation of PARNA, in addition to constant activism for its preservation	Interest in alternatives to mining activity
Ecotourism companies/freelancers	Private sector	Execution of ecotourism activities in the region	Interest in the economic benefit of ecotourism

Source: From the authors, based on the Biodiversa (2014) template³¹

This study recommends that future research use advanced technologies such as drones, HEC-RAS, and environmental modeling to expand the possibilities for analysis and planning in the study of land use and occupation. Drones, as described in^{27,28} are capable of providing images with detailed resolution, which allows for the monitoring of fragmentation and rapid changes in the landscape. HEC-RAS, in turn, allows for the assessment of the hydrological impacts of changes in land use, and is therefore an important tool for protecting aquifers and mitigating flood risks. Environmental modeling allows for the simulation of future scenarios and the identification of priority areas for conservation, as well as the recommendation of sustainable management strategies. The combination of such approaches, together with the tools used in this work, promotes a multidimensional approach to the problem and provides support for decision-making by competent authorities when faced with problems similar to the case studied.

Another recommendation is to incorporate Nature-Based Solutions (NBS) into the management of the park under study, as it promotes ecosystem conservation while offering social and economic benefits. Strategies such as ecological restoration with native species and green infrastructure for water management increase the resilience of ecosystem services, mitigate anthropogenic impacts, and foster sustainable development, as described by^{34,35}. These actions, combined with low-impact ecotourism and community engagement

programs, in addition to bringing benefits to the park in the face of environmental pressures, are aligned with global sustainability and conservation goals.

Conclusion

This study quantified changes in land use and land cover in the Serra do Gandarela region, identifying critical anthropogenic pressures and applying a systematic analysis of Landscape Ecology, in an unprecedented effort in the area. Our findings reveal a pattern of gradual and persistent replacement of natural areas by anthropogenic features, which contribute to habitat fragmentation and ecological vulnerability in a region of high biodiversity. Such a process of change not only affects local ecosystems, but also aligns with a global pattern of pressures on natural regions, standing out as a microsome of pressures faced by conservation areas around the world, as documented in the technical and scientific literature.

Furthermore, the stakeholder identification and categorization model highlights the urgent need for multi-stakeholder and democratic engagement, which is of utmost importance to balance the conflicting interests between economic development and environmental conservation. This approach allows environmental conservation to be discussed and negotiated, and is also aligned with the United Nations Sustainable Development Goals (SDGs), which propose a balance between development and sustainability.

At the international level, the findings of this study are that the Serra do Gandarela is an example of a critical landscape scenario in transition, where interventions can redefine the future of protected areas and provides a model for participatory environmental governance in other threatened regions around the world. Since it highlights anthropogenic pressures and the complex network of stakeholders, this study understands and concludes that local decisions can reverberate globally and recommends the importance of integrated and sustainable governance models capable of promoting or safeguarding the ecological resilience of landscapes.

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Conflicts of interest

The authors declare that they have no conflict of interest for the publication of this scientific article.

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