

The influence of mining in the *Quadrilátero Ferrífero*: landscape spatial-temporal dynamics

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Abstract

The *Quadrilátero Ferrífero* – QF, located in Minas Gerais, Brazil, is the main producer/explorer of iron ore in the country, occupying the worldwide leadership group in Mineral Exploration. Considering all the environmental impacts associated with this activity, it is necessary to assess the landscape patterns to support the sustainable planning of mining companies. So, this paper aimed to define the temporal changes in the QF landscape's configuration, and composition from 1985 to 2018 and predict them for 2053. We used classified images of land use/cover, from 1985 to 2018, to calculate the landscape metrics and perform the LCM tool. Thus, we executed the change analysis and prediction, to acquire the landscape patterns for 2053. To that content, we used class and landscape metric levels, especially to describe the spatial distribution of land use/cover, and to identify how its composition has changed over the years. The results show that the Forest class contributed the most to Mining, with +0.09% in the area. In addition, the Farming class decreased 12%, with its total area converted among the others land use/cover. Thus, the Forest and Mining patches' areas raised by 4% and 0.2%, with a tendency for a continuous increase until 2053. However, the forest fragments tended to disaggregate, while the Mining areas tended to become more connected. These results converge to a worrying scenario from an ecological point of view. Therefore, it is necessary to have/search for better supervision related to the compliance of environmental laws to avoid biodiversity losses in mining areas.

Keywords: Land Change Modeler; Landscape metrics; Environmental monitoring; Land use and cover; Mining companies.

1. Introduction

The *Quadrilátero Ferrífero* (QF), located in the Minas Gerais State, is a region of great historical-cultural and economic importance for its mineral resources; in addition, there is also the well-known soapstone, used in many architectural projects of the surrounding municipalities. Furthermore, the denomination QF is associated with the quadrangle geometric shape of the elevated morph-structural block in the region (Azevedo et al., 2012). In its coverage area, there are numberless ethnographic, archaeological, and environmental heritages (rock outcrops, forest areas, and grasslands), besides World Heritages, such as *Serra da Piedade* and *Pico do Itabira* Geological Sites. There are also protected areas known as *Unidades de Conservação* – UCs (Bustamante and Gonzalez, 2017). Furthermore, the QF is the main producer/explorer of iron ore in Brazil, with approximately 70% of the total production, occupying the worldwide leadership group in Mineral Exploration (Spier et al., 2019;

IBRAM, 2021b). These characteristics associations require ongoing studies and researches about the pattern assumed by exploring and conserving the natural resources in the region.

Exploration of iron ore causes intense changes in the landscape, which directly affects the land cover. Its major impacts occur due to the construction of tailings dams, the concession of mines licenses, and the lack of commitment to restoring degraded areas. Leading to the fragmentation of forest areas and results in the lowering of groundwater, alteration of slope in mined areas, and the decrease in the flora and fauna diversity (Camargos et al. 2019; Rezende, 2016). However, these activities also provide uncountable social, economic, cultural, and environmental benefits, such as employment generation, poverty reduction, and public education improvement. Both for the surrounding communities and the entire country due to the direct influence exerted by the QF on the steel companies that promote the entire national industrial chain (Terama et al., 2016).

Therefore, there is a dilemma that mining companies seek to address "How to mine sustainably and ensure landscape maintenance?" Studies by Florkowska and Bryt-Nitarska (2018) showed that mining companies have the financial and technological conditions to do so; however, there is a need to commit to legal standards that they are liable to and greater planning. Furthermore, Okado and Quinelli (2016) indicated the lack of homogeneity of standards and legislation between countries related to the sustainable exploration of iron ore, which creates countless gaps and facilitation for the loosen development of this activity.

Studies about land cover dynamics and use are necessary to obtain extensive knowledge about the range of impacts for this type of exploration. Especially when considering that these are the most important anthropogenic precursors for assessing environmental changes at all spatial and temporal scales (Garcia et al. 2019; Gomes et al. 2020), in this way, researchers and Public Policy developers need to oversee and mitigate the negative consequences of this dynamic. At the same time, it is also necessary to maintain the production/exploitation of essential natural resources, especially when taking into account the important role of Brazil in the exploration of minerals worldwide, besides the recent accidents and environmental crimes involved in this sector (Garai and Narayana, 2018; Monteiro et al. 2019; Urbano et al. 2020).

The temporal analysis of landscape structure, considering land use and cover, has fundamental importance to the evaluation and planning of productive activities, whether in the short or long term, especially when dealing with areas influenced by Mining and agriculture, like the QF (Azevedo et al. 2012; Feurdean et al. 2017; Garai and Narayana, 2018; Chen et al. 2018). For that matter, the combination of geotechnologies such as Geographic Information System (GIS) and Remote Sensing (RS) presents itself as an important tool for landscape studies. Mainly due to the method's practical and low-cost nature, data acquisition becomes more accessible, and field trips are only necessary to validate the information obtained (Encina et al., 2018).

In addition to these geotechnologies, it is common to use some quantitative parameters, called landscape metrics, which allow knowing the spatial patterns and temporal dynamics of landscape and the association of this information with the ecological processes in the study area (Turner, 1989). The main components of this type of analysis are matrix (predominant class), fragments or patches, and corridors; its function is to verify the interactions between the classes that compose it; and its dynamics reflect changes in structure over the temporal,

historical period (Forman and Godron, 1986). Thus, the application of these metrics guarantees the quantification of fragmentation degree in the landscape (Cachoeira et al. 2020).

Moreover, the Land Change Modeler – LCM is a tool that also presents fundamental relevance in the study of landscape, as it allows to perform projections and evaluation of changes in its structure, especially for land use and cover planning (Eastman and Toledano, 2018; Ferchichi et al. 2018). To this end, based on a historical change in land cover, empirical modeling is executed to reflect the relationship between the transitions of pertinent cover classes and explanatory variables to map future scenarios of change for exploration, conservation, and environmental sustainability (Jain et al. 2017; Eastman and Toledano, 2018; Leta et al. 2021). In this way, the LMC represents a powerful GIS tool applied to monitoring, change assessment, and future projections.

In this context, this study contributes to understanding the landscape Mining dynamics to verify and predict the impact over the decades, based on actions taken and their interference in the environment. Therefore, this work aimed to determine the temporal changes that occurred in the configuration and composition of the QF region landscape, in Minas Gerais State, based on the Forest and Mining areas spatial patterns, from 1985 to 2018, in addition, to perform a projection of these same parameters for the year 2053.

2. Material and Methods

Study area

The QF region, located in the Center-South of the Minas Gerais State, is the largest national producer of iron ore with approximately 70% of the total production, and exploration of gold and manganese, but in a smaller proportion. It has an exploration area equivalent to 7,000 km² and covers an indirect impact area greater than 19,000 km², distributed among 57 municipalities: Alvinópolis (1), Antônio Dias (2), Barão de Cocais (3), Bela Vista de Minas (4), Belo Horizonte (5), Belo Vale (6), Betim (7), Bom Jesus do Amparo (8), Bonfim (9), Brumadinho (10), Caeté (11), Casa Grande (12), Catas Altas (13), Catas Altas da Noruega (14), Congonhas (15), Conselheiro Lafaiete (16), Diogo de Vasconcelos (17), Entre Rios de Minas (18), Ibitiré (19), Igarapé (20), Itabira (21), Itabirito (22), Itatiaiuçu (23), Itaúna (24), Itaverava (25), Jeceaba (26), João Monlevade (27), Juatuba (28), Lamim (29), Mariana (30), Mário Campos (31), Mateus Leme (32), Moeda (33), Nova Era (34), Nova Lima (35), Nova União (36), Ouro Branco (37), Ouro Preto (38), Piedade dos Gerais (39), Piranga (40),

Queluzito (41), Raposos (42), Ribeirão das Neves (43), Rio Acima (44), Rio Manso (45), Rio Piracicaba (46), Sabará (47), Santa Bárbara (48), Santa Luzia (49), Santa Maria de Itabira (50),

Santana dos Montes (51), São Brás do Suaçuí (52), São Domingos do Prata (53), São Gonçalo do Rio Abaixo (54), São Joaquim de Bicas (55), Sarzedo (56) e Vespasiano (57), as it shows in Figure 1.

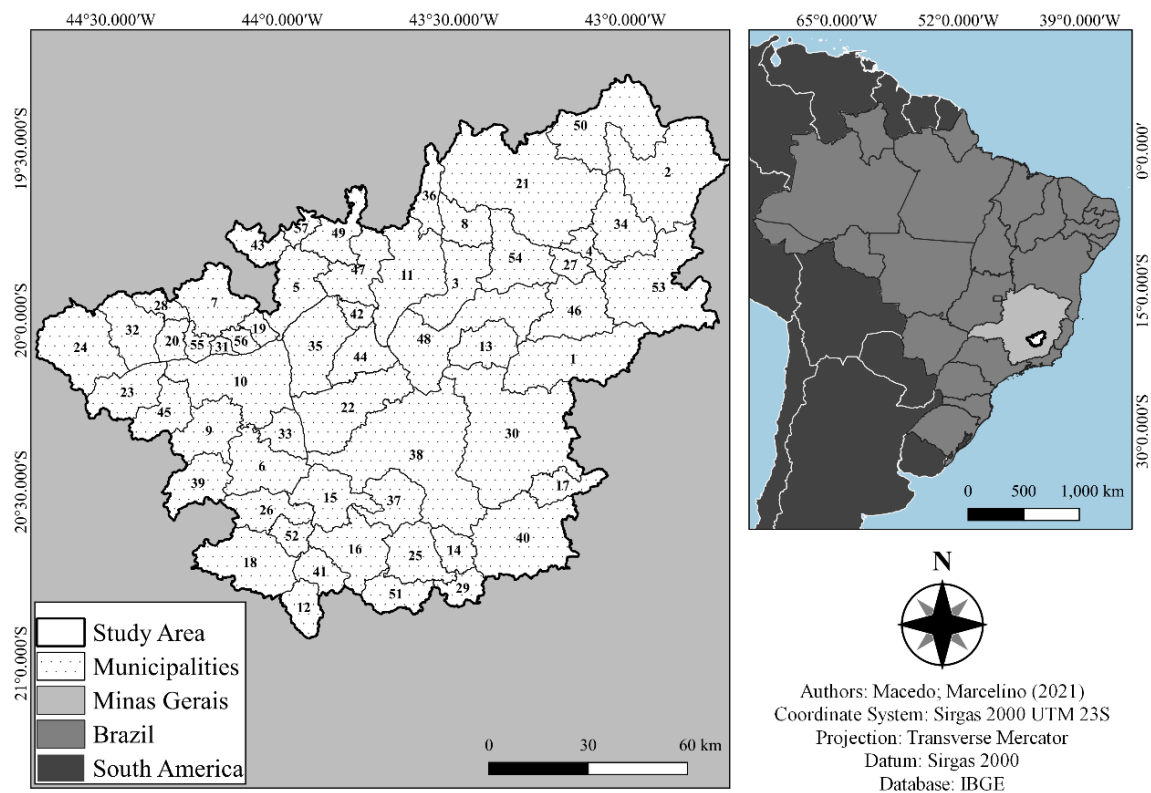


Figure 1 - Location and municipalities of the Quadrilátero Ferrífero (QF), Minas Gerais, Brazil.

The region presents an annual average temperature of 20 °C, and annual precipitation between 1300 mm and 2100 mm (Barros and Magalhães Junior, 2018, 2019). Thus, the prevailing climate is warm-temperate, with two well-defined seasons, dry winter and rainy summer, of the Cwa/Cwb type, according to the Köppen classification, mainly due to the different microclimates generated thanks to the existing morpho-structural diversity (Menezes et al. 2019).

According to a mapping carried out by the Brazilian Institute of Geography and Statistics, Directorate of Geosciences (IBGE, 2006a), the natural vegetation of the QF region is composed of Seasonal Semideciduous Forest, in addition to Savanna and an extensive contact region (transition

zone between the types of vegetation). Furthermore, the local soils have a clayey texture, with a predominance of the following types, according to the Brazilian Classification System: Latossolo, Cambissolo, and Argissolo (IBGE, 2006b).

Database

The database for the landscape characterization consisted of land use and cover images (Figure 2), available in the MapBiomias Project (MapBiomias, 2021a), generated from LANDSAT orbital satellite with a spatial resolution of 30 m. In Mapbiomas (2021b) is possible to access classification details. The temporal analysis was from 1985 to 2018, corresponding to an interval of 33 years. The raster images refer to Collection #5, MapBiomias' most recent database.

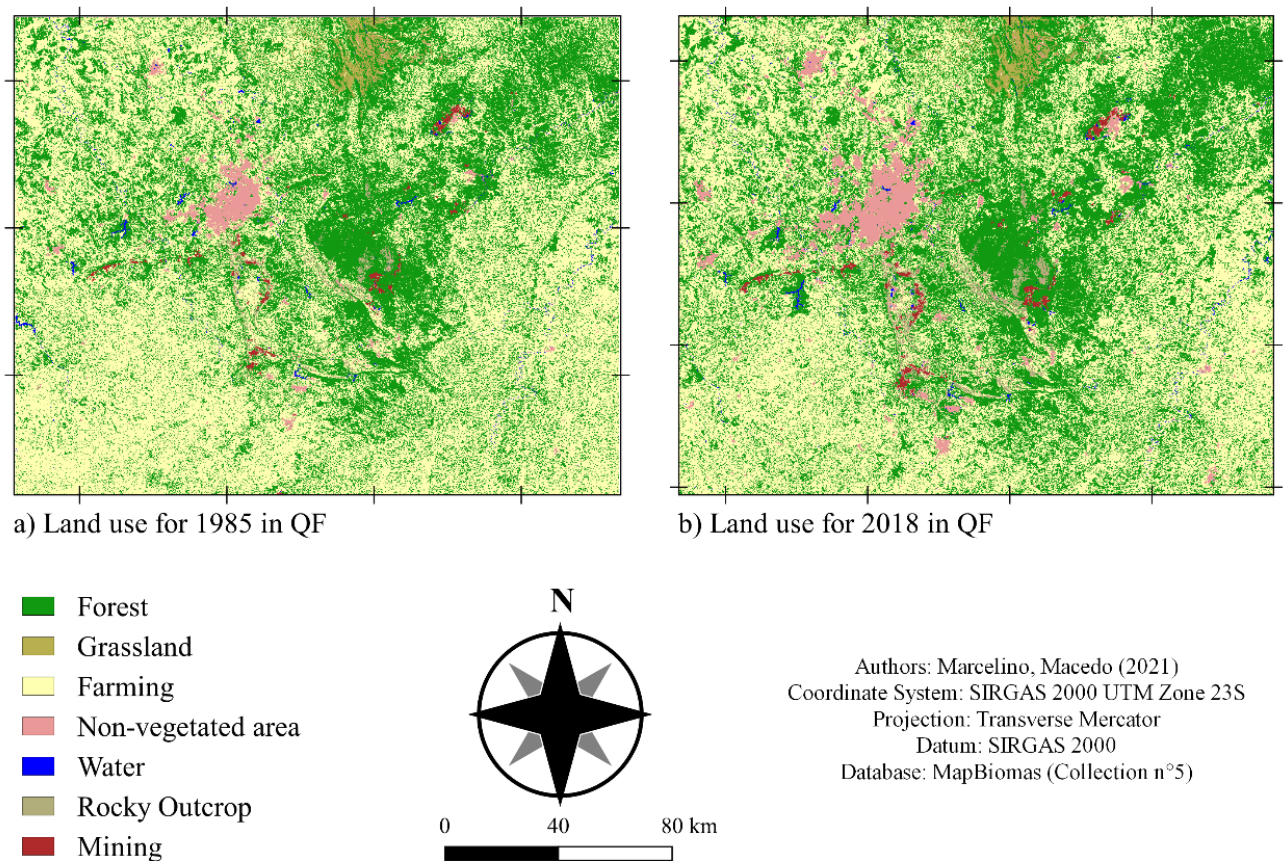


Figure 2 - Representation of land use and cover classes according to MapBiomass data for the QF in 1985 (a) and 2018 (b).

The elevation model used in this research was from the Shuttle Radar Topography Mission - SRTM dataset prepared in partnership with the National Aeronautics and Space Administration - NASA and the National Geospatial-Intelligence Agency - NGA, file USGS EROS - Digital Elevation - SRTM 1 Arc-Second Global. Its use is justified by the location of the mined areas that occur in elevated regions (USGS EROS, 2021). All data had a spatial resolution of 30 m.

The database was prepared in the GIS environment using QGIS 3.16.4, a free and open-source software (QGIS, 2021). In this environment, pre-processing and georeferencing steps of the raster files were performed, such as the delimitation of the study area and conversion to matrix and vector formats. Finally, to analyze the spatial-temporal dynamics of the landscape, we selected and regrouped the vegetation areas into the following classes: Forests, Grassland, Mining, Non-Vegetated Areas; Rocky Outcrops; Farming and Water. For the prediction in the LCM sub-model, the Mining class was considered under the influence of all others. For the analysis of Landscape Metrics, the classes considered were Forests and Mining.

Class Mapping by Land Change Modeler – LCM

The LCM was used to quantify and map the land use classes that showed area losses or gains, besides the most significant changes in the QF region (TerrSet LCM, 2021). The steps to the analysis and modeling were Change Analysis, Transition Potentials, and Change Prediction (Validation and Prediction). To structure the sub-model, we use the Multilayer Perceptron - MLP Neural network technique for the future prediction of the Mining class.

The LCM tool uses the Markov Chain to calculate the transition from one use class to another based on the historical land cover change of the "previous" and "post" images. In this study, we use images of 1985 and 2018, organized in the same groups of classes. The Digital Elevation Model (SRTM) was considered to assist in the modeling, as Mining occurs in higher elevations, a dominant characteristic of the region. For model validation and subsequent prediction, we use the 2019 image. The year chosen for future analyzes was 2053, as this is the same time interval used to determine changes in the past (33 years). Moreover, the study region

presents numerous potential sites for the concession of new mines for Mining, guaranteeing more decades of exploration and great prospects for its expansion, as observed by Rezende (2016) and IBRAM (2021b).

The changes in the classes in the evaluated period and the contributions and interrelationships

were also compared using the LCM. Finally, the validation accuracy was determined using the Kappa statistic (Table 1), referring to the points of agreement/disagreement, and the Root Mean Square Error - RMS of training and test of the model generated.

Table 1 - Interpretation of Kappa values for validation of the LCM model generated for the land use and cover classification.

Kappa Values	Interpretation
< 0	Total Disagreement
0.00 – 0.19	Poor Agreement
0.20 – 0.39	Fair Agreement
0.40 – 0.59	Moderate Agreement
0.60 – 0.79	Substantial Agreement
0.80 – 1.00	Almost Perfect Agreement

Source: Landis and Koch (1977).

Landscape metrics

The land use and cover images were submitted to the FRAGSTATS v4.2 software, the latest version, Spatial Pattern Analysis Program for Categorical Maps, responsible for computing a wide variety of landscape metrics for categorical map patterns (McGarigal et al. 2012). These calculations were performed at three-year intervals between the period 1985 and 2018. As a result, it was possible to quantify the spatial-temporal dynamics of the QF landscape without an excessive amount of data, facilitating its compilation and subsequent analysis.

Considering that the landscape has two main components: the discontinuous units with characteristics that differ from their surroundings (patches) and the element of greater extension and connectivity, whose effect is predominant over the others (matrix) (Siqueira, Castro and Faria, 2013), it was necessary to determine which classes of land use, and cover would represent these structural units. Thus, the present study was carried out under two approaches. The Forest class first received the attribute of "patches", with the other classes being defined as the landscape's "matrix". In the second approach, the Mining class came to be considered the focal patch to evaluate this class's structural and

spatial behavior in the landscape over the years and associate these results with those of forest fragments.

The parameters used followed the description proposed by McGarigal (2015), whose main information is listed in Table 2.

It is necessary to emphasize that, for the Mean Core Area Index (CAI_MN) calculation, edge values - which represent the reach of the matrix effects over interest patches - are required. On this account, according to Murcia (1995), in a landscape, dissimilarities in the composition of the neighborhood can cause harmful effects on the biodiversity of a habitat patch, known as edge effects. Unfortunately, however, there is no consensus on the method for determining these edge measurements, which makes their choice somewhat arbitrary (McGarigal and Marks, 1995).

Considering the existing heterogeneity between land use and cover' classes of the QF region, we used different distances from edges according to each class's composition and anthropization degree. The values ranged from 0m, for classes with little or no effect, to 90m, for the most hostile class, such as Mining (Table 3). Thus, the interval used between edge distances was 30m, representing the pixel size (the smallest unit that composes the raster image).

Table 2 - Landscape metrics were used to assess the spatial dynamics of Mining and Forest areas in the Quadrilátero Ferrífero - MG from 1985 to 2018.

Group	Landscape Metrics	Description	Range	Unit
Area	Class Area (CA)	The sum of the area of each class.	$CA > 0$	ha
	Percentage of Landscape (PLAND)	Defines the percentage of area occupied by each class based on the total landscape area.	$0 < PLAND \leq 100$	%
Shape	Mean Shape Index (SHAPE_MN)	The ratio between perimeter and patch area. The closer to 1, the more regular the patch shape.	$SHAPE_MN \geq 1$	-
Core Area	Mean Core Area Index (CAI_MN)	The average percentage of core present in each patch is the region not affected by edge effects.	$0 \leq CAI_MN < 100$	%
Aggregation	Euclidean Nearest Neighbor Distance (ENN_MN)	Measures the average isolation degree of patches on the landscape by comparing the distance and the total number of patches of the same type.	$ENN_MN > 0$	m
	Aggregation Index (AI)	The occurrence of patches of the same type side by side in the landscape. AI = 0, when the landscape is fully disaggregated.	$0 \leq AI \leq 100$	%
	Patch Cohesion Index (COHESION)	Represents the connectivity of patches in the landscape. COHESION = 0, when the landscape is physically disconnected.	$0 < COHESION < 100$	-
	Number of Patches (NP)	The number of patches present in the landscape.	$NP \geq 1$	-
	Patch Density (PD)	Determines the number of patches per unit area.	$PD > 1$	No/ 100 ha
	Splitting Index (SPLIT)	Indicates the subdivision of the landscape into patches. SPLIT = 1, when the landscape is composed of a single patch.	$SPLIT \geq 1$	-
Diversity	Patch Richness (PR)	Consider the number of different types of patches present in the landscape.	$PR \geq 1$	-
	Patch Richness Density (PRD)	Indicates the number of different types of patches per unit of area in the landscape.	$PRD > 0$	No/ 100 ha
	Shannon's Diversity Index (SHDI)	Determines the heterogeneity of the landscape based on the different types (classes) of patches that compose it.	$SHDI \geq 0$	-
	Simpson's Diversity Index (SIDI)	Represents the probability of finding different types of patches on 2 randomly selected pixels.	$0 \leq SIDI < 1$	-

Table 3 - Edge distance values were adopted to calculate the Mean Core Area Index (CAI_MN) metric, based on the effect exerted by each class on the Forest areas of the QF.

Land use and cover	Edge effect (m)
Forest	0
Grassland	30
Farming	60
Non-Vegetated Areas	60
Water	0
Rocky Outcrop	30
Mining	90

The obtained results were compiled and related to each other. As a result, information about possible changes in the landscape from 1985 to 2018 could be extracted and a future analysis based on the projection map for 2053, modeled from the LCM.

3. Results and discussion

Temporal dynamics and future projection by Land Change Modeler - LCM in the QF

Based on the application of the LCM tool, it was possible to observe differences in the land use

and cover of the QF region for the evaluated period (Figure 3). There was a predominance of Farming, Forests, Non-Vegetated Area, and Rocky Outcrops due to the area's landscape heterogeneity and soil exploitation history. It is also possible to note that the Mining class was located at the highest elevations, centralized in the region, with greater interference in the areas of Rocky Outcrops and Forests. Farming areas contributed the most to transforming the soil into Non-Vegetated Areas, places where urban areas predominate.

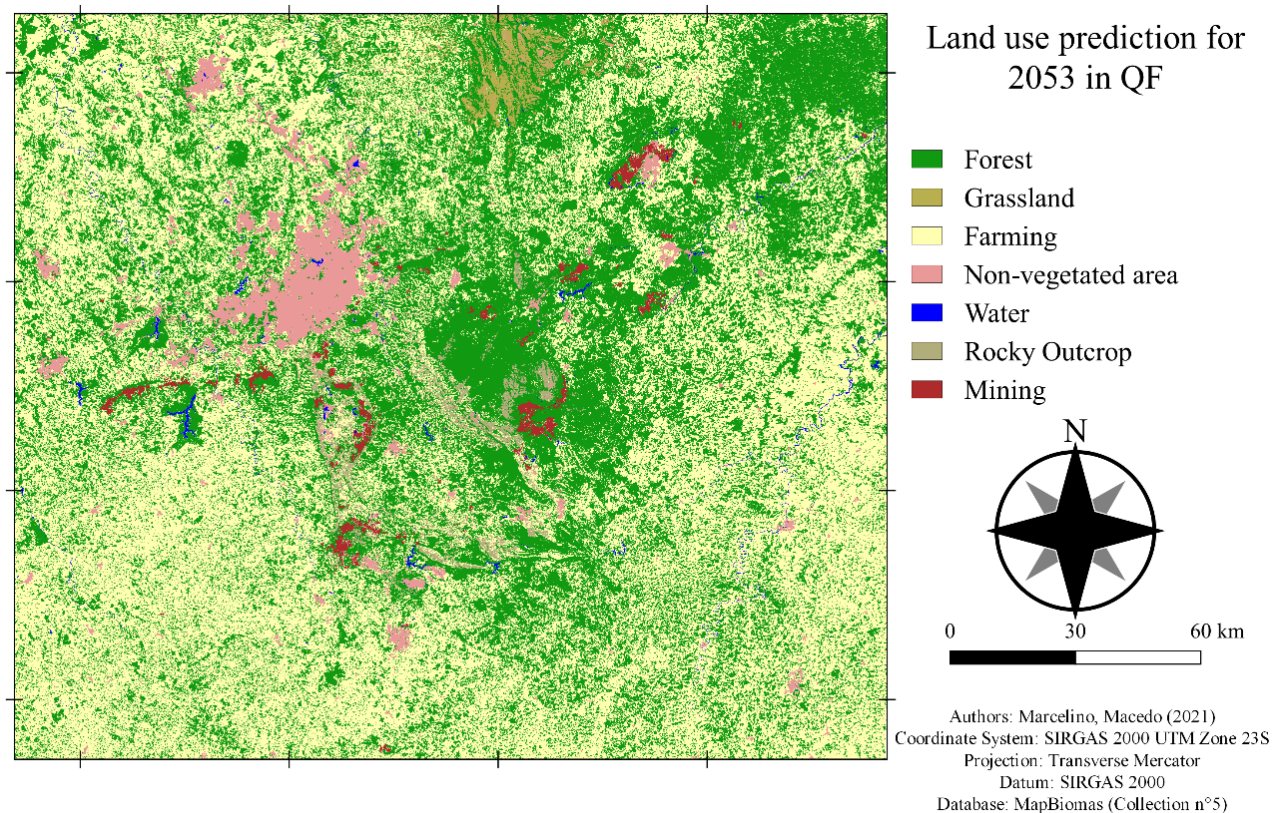


Figure 3 - Representation of land use and cover classes in the QF, predicted by the LCM sub-model for the year 2053. Source: Authors (2021).

The model generated from the LCM analysis was accurate, with an almost perfect agreement, Landis and Koch (1977), and allowed the observation of important results for the monitoring and future projection of land use and cover in the QF, mainly to verify the advance and behavior of Mining in this region. Furthermore, the spatial pattern of the Forest class near the mined areas tended to maintain. Table 4, shows the results that reflect the quality of the model used in this study, whose indexes presented

high values of reliability and accuracy. The areas of interaction between the Farming and Forest classes were the most complex because their change was related to other factors, such as the form of advance and/or retreat, larger total areas of impact, and land exploitation, which interfered in the statistics of the model. However, these data held up with high reliability for the future prediction of Mining in the QF.

Table 4 - Statistics of the generated LCM sub-model for the future prediction of Mining in the QF region.

Statistic	Sub-model LCM
Training RMS	0.064
Testing RMS	0.065
Accuracy (%)	96.800
Kappa	0.943

Figures 4 and 5 present the results obtained from the LCM for the land use and cover classes of the QF about monitoring and evaluating changes in the landscape as a percentage of the total study area. The Farming and Forests classes underwent the greatest changes (Figure 4a) and, consequently, showed the greatest losses and gains, with -12% and

+10%, respectively (Figure 4b). Thus, showing both soil exploitation by crops and a greater increase in natural or planted forests in the region of the QF for the period evaluated. It is also worth mentioning that there was considerable variation in the class Not Vegetated, with an increase of almost +2% in area, and Mining of +0.17%.

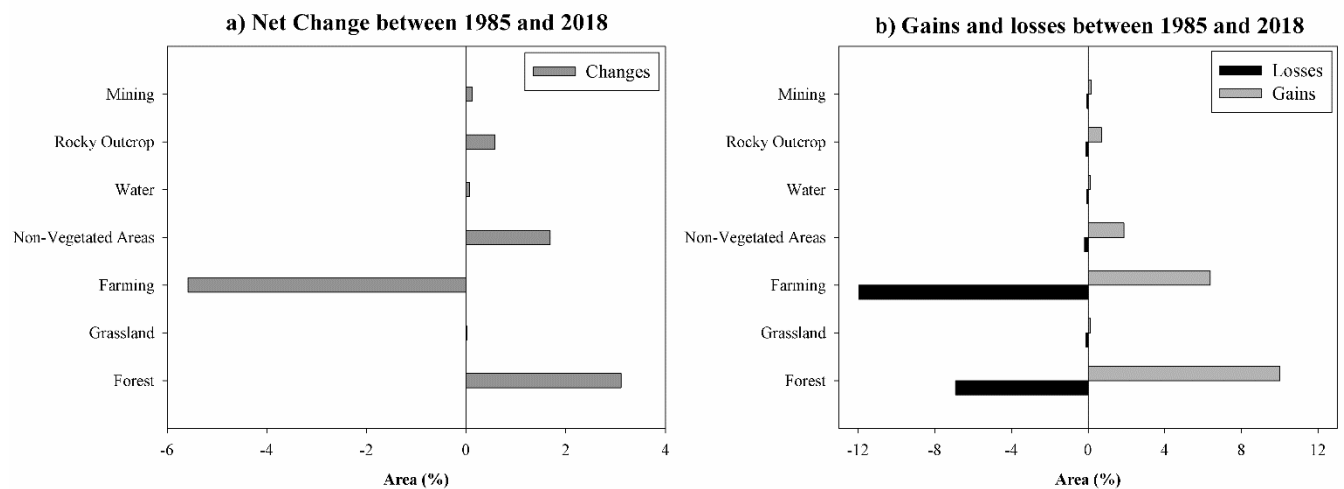


Figure 4 - Changes recorded in the land use and cover classes of the QF landscape between 1985 and 2018: a) Absolute changes in areas; b) Gains and losses of each class.

Furthermore, the Forest class has contributed the most, from past to present, to Mining areas. According to the model prediction for 2053 (Figure 5a), it will contribute in the future, being responsible for an increase of 0.09 0.2% in area, respectively. The Farming class is immediately after, with a contribution of 0.04% for the past period and 0.08% for 2053. Another important factor about this class was the sharp decrease in its original territory, for which there was no increase in the evaluated period, only transition to the other classes. The most

significant contributions were to the Forests and Non-Vegetated Areas, with 0.04% and 0.02%, for both classes, respectively (Figure 5b). On the other hand, the areas that underwent the least changes were the Grasslands, which remained constant throughout the evaluated period, mainly because of their location in the region's northern part and being inserted in protected areas UC.

This study highlighted the effects of Mining on the QF landscape, resulting in several changes, mainly in forest areas. However, it is also noted that

the Farming areas are associated with the landscape fragmentation process, evidenced by the monitoring data of changes in land use and occupation classes, where there were reductions in Farming and increases in mined and forested areas. These results determine important aspects for the future of the QF. Therefore, they should be considered in decision-making, especially by large land properties of agricultural and Mining use in the region, which total more than 3,000 units, just by mining companies (IBRAM, 2021a, 2021b). Gazzinelli (2021), evaluating the impacts of these Mining companies in Minas Gerais, indicated that there are still numerous barriers from the environmental and social point of view to be considered by the companies in this sector. In addition to the risks imposed by them and the state authorities to the living conditions of the surrounding communities.

Considering that, for this research, the Forest areas are the main class impacted by the Mining increase, there is a relevant dilemma in the discussions around this sector, short and long term. According to studies by Tonietto and Silva (2011) and Rezende (2016), which verified the impact of extraction, mainly of iron ore, in addition to the region's endless potential for this type of exploitation in the future, it was reported that a large part of the Atlantic Forest remnants belongs to mining companies. Therefore, due to the high level of threat to this biome in Brazil, its maintenance and the application of environmental fines proportional to the damage caused by these activities is necessary. Still, according to these authors, in the Mining activity, the cost of recovering the exploited site represents approximately 1% of the total investment, which makes it fundamental to demand environmental inspection and expertise about the non-compliance with the required standards.

Another result in this research was the increase in the areas occupied by Forests and Mining, with the highest peaks observed after the year 2006 for Forests and after 2012 for Mining. These increases can be justified by: economic fluctuations in the country; increases in the demands of iron ore exploration and exportation, especially in Minas Gerais (the largest producing state); increase in planted forests in the steel industry sectors for the production of charcoal; increase in planted forests areas in Brazil, especially in Minas Gerais (the state with the largest planted area), associated with large companies and independent rural producers; the elaboration and updating of Norms and Decrees of a Legal nature regarding the maintenance, conservation, and recovery of degraded areas, whether by Mining or Farming; the increase in the maintenance of natural areas of public and private properties into protected areas; the drastic

infrastructure and socioeconomic changes in the country (urbanization) and the increase of companies in the sector directly and indirectly linked to Mining. These events can be found in the studies of Rezende (2016); Diniz et al. (2014); Ribeiro et al. (2018); IBA (2021); Tonietto and Silva (2011); IBRAM (2021); IBRAM (2021b); Gazzinelli (2021).

Moreover, the QF, for being a region of great historical-cultural and economic importance for the whole country, has a high potential for the creation and preservation of conservation areas, besides the possibility of having points classified as Cultural Heritage of the society. These discussions have been going on for decades (Azevedo et al., 2012). And, because it is a region composed of countless Sierras, UCs of great relevance for the entire macro-region of the QF were created (Marent et al., 2011; Rezende, 2016; Diniz et al. 2014; Bustamante and Gonzalez, 2017). The creation of these UCs favored the increase of Forest class due to pressure from environmentalists and the elaboration and updating of Environmental Laws, influencing the decrease in Farming areas. Furthermore, the increase in planted forests on rural properties also affected the evaluated period, favoring the increase in forest areas.

Another extremely important factor regarding the increase of Forest areas and consequent decrease in Farming is related to the fact that QF is in a transition zone between the Brazilian Cerrado and Atlantic Forest biomes. Due to the strict control through Norms and Decrees of the State Government, which since 2005 prevents or makes it difficult to grant licenses and authorizations to suppress native vegetation, especially in the Atlantic Forest biome, there was a decrease in the deforestation rates for the evaluated period. Moreover, the suppression of native areas has remained constant in recent years, according to the technical report SOS Mata Atlântica (2021), which shows that these guidelines are having a positive effect in the region, an extremely important factor from an ecological point of view. Still, it does not guarantee 100% effectiveness for its continuity.

However, it is noted that the mined areas in the QF region are located within or near UCs and the location of future mines to be licensed, which exerts strong pressure from mining companies on these areas concerning their fragmentation. As demonstrated in the contribution results of the Forest class to Mining. Thus, establishing more effective conservation practices during the licensing process of native areas and the post-mining recovery of mined areas becomes necessary and crucial to maintain these related areas. Such as ecological corridors to ensure the flow of fauna and flora, avoiding the collapse of areas intended for conservation and preservation, as discussed by Diniz et al. (2014) and Ferreira et al. (2020).

Another problem linked to the conservation and preservation of Forests and the entire historical and cultural heritage of the QF region shortly relates to the intense and growing advance of urban areas, represented by the classes of Non-Vegetated Areas, with expressive results verified in this study. Furthermore, since the areas available for construction of new condominiums are those of public domain, therefore the Forest areas, since those for agricultural use are mostly of a private domain, authors such as Ercoli et al. (2020) and Ferreira et al. (2020) discussed this subject and established crucial relation of the rapid and disorganized growth of the municipalities, especially in this region, which also puts the surrounding natural areas at risk, including those belonging to the UCs, have discussed these.

Allied to this, the Mining activity in Brazil is regulated by a series of extensive and, most of the time, conflicting norms, which establish barriers for its practical application. In general, the exploitation

of mineral resources is related, mainly, to the growing and ongoing international competition and the demands of the export market, which, due to environmental pressures, require increasingly strict environmental standards in the search for a green economy. Rezende (2016), in his study, noted that generally, the rules and laws that regulate all Mining processes in underdeveloped countries tend to be less strict. Consequently, there is antagonism. Theoretically, following the Local Legislation does not mean that a good practice occurs, making foreign sales or the international market a real brake on environmental actions in the exploration areas. Another impasse is the Mining's high proximity to the Forests, which increasingly requires sustainability actions and the application of effective environmental education in the surrounding Municipalities, aiming to maintain the biodiversity of the FQ, which is threatened.

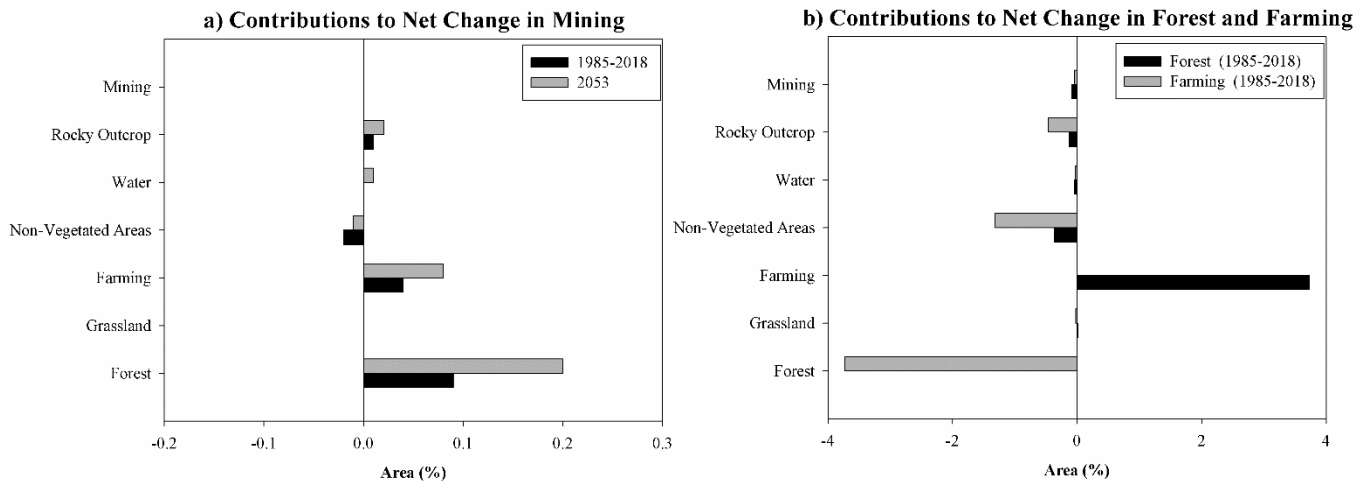


Figure 5 - Contribution of land use and cover classes to the changes in the areas: a) Mining; b) Forest and Farming.

Spatial-temporal dynamics by landscape metrics in the QF

Regarding the landscape metrics, the results obtained about the spatial-temporal dynamics of the Forest and Mining patches are shown in Figures 6, 7, and 8. Based on the structural parameters of the landscape from 1985 to 2018 (Figure 6), the Forest class showed the highest area (CA) and occupancy percentage of landscape (PLAND) than the Mining class, with average values of approximately 900 000 ha and 45%, respectively. Concerning the temporal changes for these metrics, the landscape composed percentage of forest fragments assumed a sharp

growth (4%) after the year 2006, with a tendency to stabilize after 2015, without reaching 50% of the total area of the QF. In contrast, despite representing less than 1% of the landscape, there was an accentuation (variation of + 0.2%) in the curve of mined areas after the year 2012, reaching values higher than in previous years. Thus, highlighting the close relationship between these classes, as already reported in the LCM results. The predictions for 2053 indicate that Mining areas tend to increase approximately 0.4%, almost double the previous variation, while Forest areas demonstrate a lower change, with an increase of 0.06%.

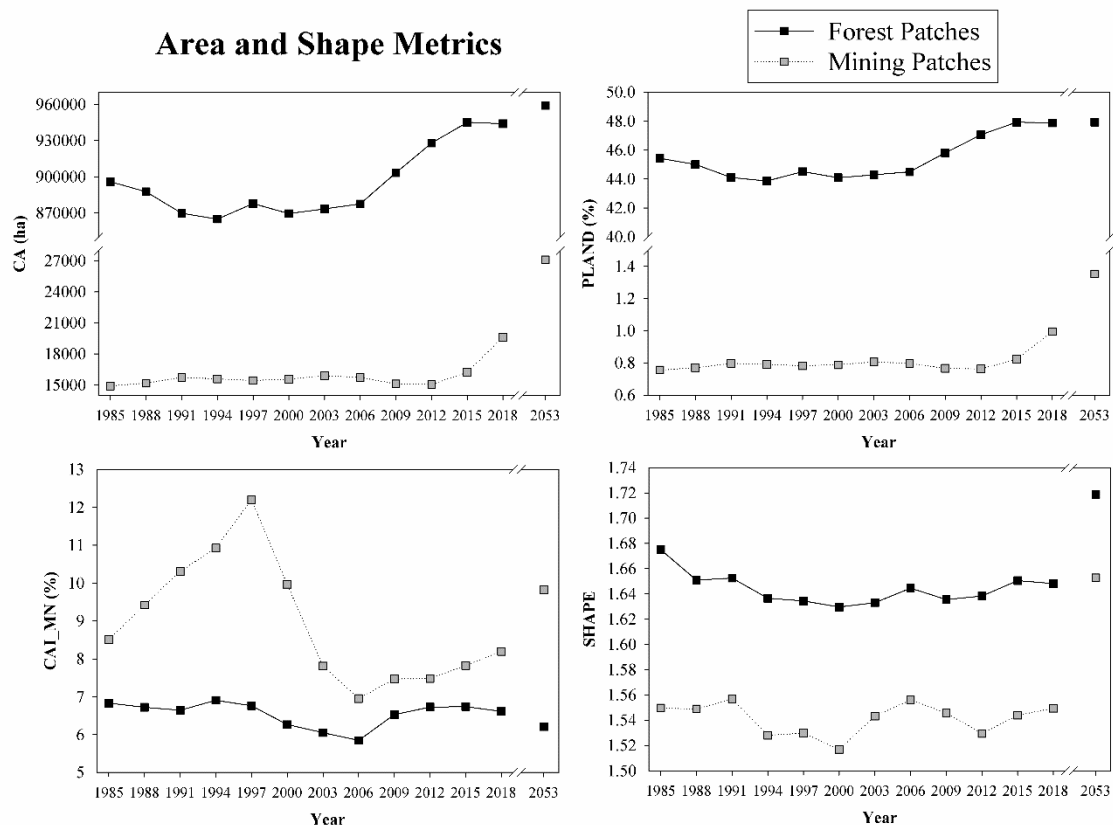


Figure 6 - Area and shape metrics of Forest and Mining patches for the QF, from 1985 to 2018, and projection to 2053; CA (ha): Class Area; PLAND (%): Percentage of Landscape; CAI_MN (%): Mean Core Area Index; SHAPE: Mean Shape Index.

Oppositely to the total area results, core area values (CAI_MN) of Mining patches proved to be higher than the ones of the Forest class, averaging 8.92% between 1985 and 2018, even with a decline observed between 1997 and 2006. Furthermore, its core was 2.4% larger despite less significant coverage because it does not suffer from border effects, like Forest class. Thus, the trend for the coming years is that there will be a 0.4% decrease in the core area for forest fragments, resulting in patches increasingly affected by the matrix pressures. In contrast, Mining areas will have increasingly larger cores.

Considering the results of patch shape (SHAPE), Forest fragments structures were more complex, while the Mining areas maintained a homogenous pattern, even with obvious fluctuations over the years. However, the values projected for 2053 indicate that both classes may assume more irregular shapes, further and further away from the standard shape (SHAPE=1). The Mining patches may reach the same parameter already assumed by forested areas in the past.

The aggregation metrics (Figure 7), in turn, denote that the Forest patches proved to be more numerous in the landscape (NP), averaging 29,000 patches, as well as being about 57 m closer

(ENN_MN) than the mining areas. Thus, the density (PD) of forested areas in the QF landscape was more notable than Mining, with average values of 1.48 and 0.05 N/100ha, respectively, from 1985 to 2018. However, the future projection shows that the NP values of Forests tend to decrease by 345. At the same time, the distance between these patch' types will increase by approximately 0.3 m, and, consequently, its density in the landscape will reduce by 0.04 N/100ha. On the other hand, the mined areas will have less distance between them, but due to the considerable decrease (from 1098 to 911 patches), they will have a lower density for 2053.

The results of the spatial configuration of patches, from 2006 on, show that it is possible to notice a tendency of QF Forests to aggregation since the AI and COHESION values increased, while the division index decreased (SPLIT). For the Mining class, however, this aggregation could only be noticed from the year 2012 onward. Although this scenario may be reversed, as the prediction for 2053 indicates a disaggregation of the Forest patches, landscape connection metrics showed decreases. Its SPLIT values increased, while Mining areas follow the opposite direction and may exceed the Aggregation Index of the Forest patches.

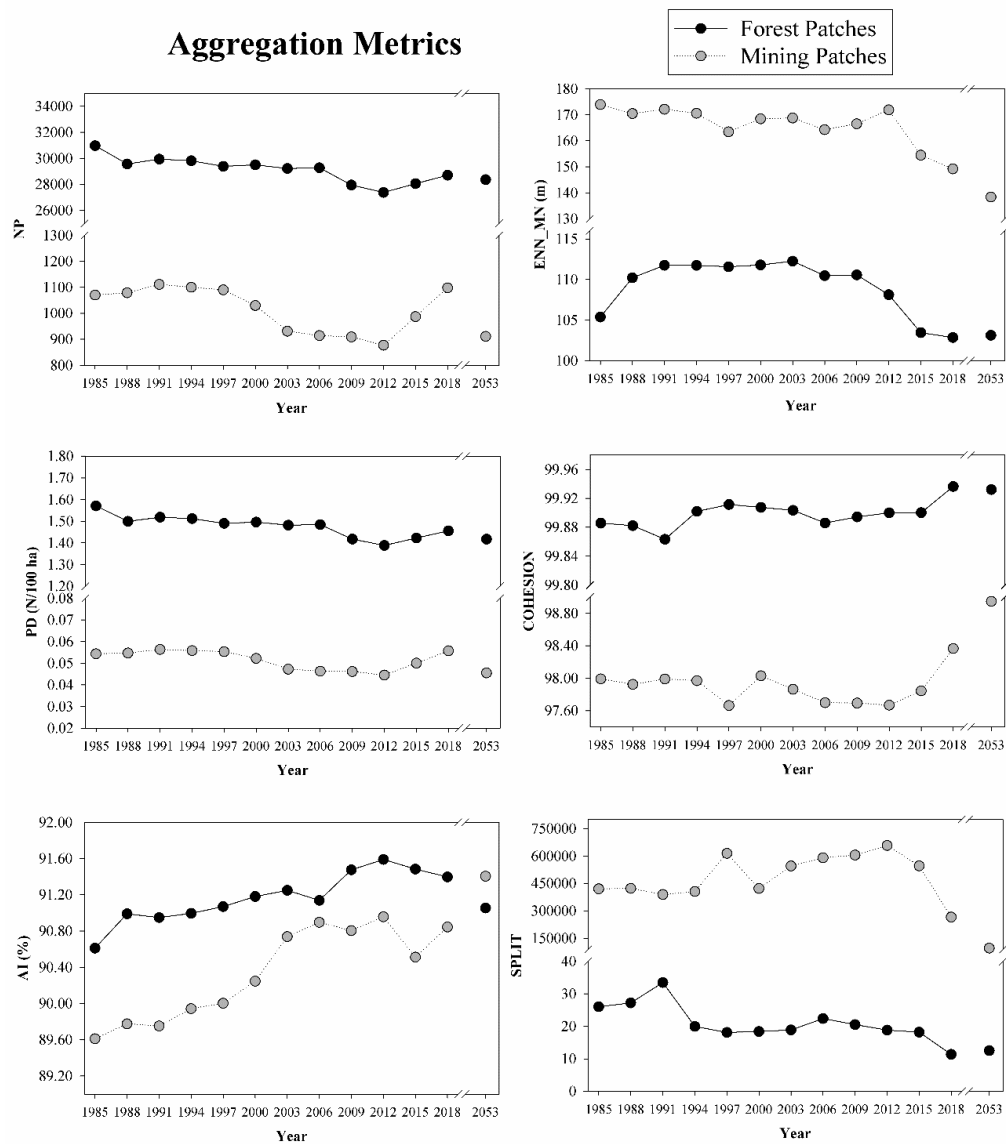


Figure 7 - Forest and Mining aggregation metrics for the QF, from 1985 to 2018, and projection to 2053; NP: Number of Patches; ENN_MN (m): Euclidean Nearest Neighbor Distance; PD (N/100 ha): Patch Density; COHESION: Patch Cohesion Index; SPLIT: Splitting Index; AI (%): Aggregation Index.

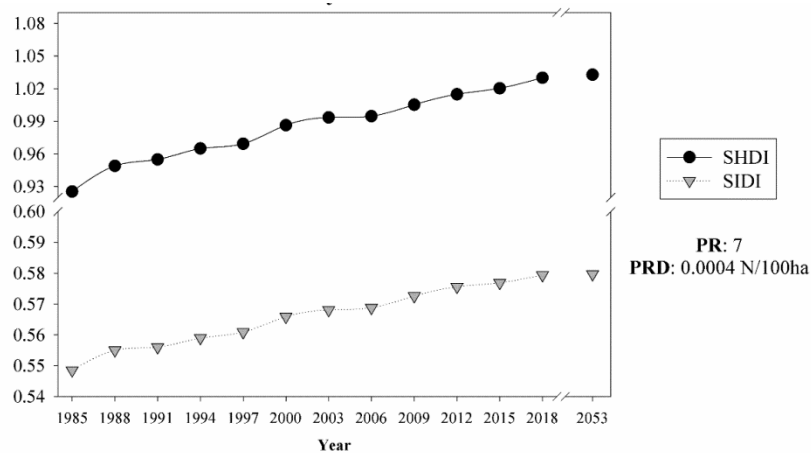


Figure 8 - Forest and Mining diversity metrics for the QF, from 1985 to 2018, and projection to 2053; SHDI: Shannon's Diversity Index; SIDI: Simpson's Diversity Index; PR: Patch Richness; PRD (N/100 ha): Patch Richness Density.

When analyzing the landscape composition (Figure 8), encompassing all seven land use and cover classes evaluated in this study, the QF has become more heterogeneous in its composition over the years. The increasing values can be seen in the Shannon and Simpson diversity indexes (SHDI and SIDI). However, the trend for the coming years is stabilization in these values, indicating that the landscape is not expected to undergo as many changes in its composition. Similar characteristics to that observed in 2018.

The Mining and Forest patch metrics and the increased landscape heterogeneity of the QF evidence that result. As reported previously, in addition to the expressive Mining areas growth starting in 2012, there was also an increase in the patches aggregation starting in the same year, even though there were variations throughout the evaluated period. On the other hand, Forests had their largest increase in the area starting in 2006, peaking in 2015. This prominence assumed by Mining in the landscape coincides with the period of Brazil's trade balance in the Technical Reports of the Brazilian Mining Institute - IBRAM for the same period evaluated. The report shows that mineral exploration has been gradually increasing in recent years and plays a prominent role in the surpluses of the Brazilian Balance. However, it suffers intense pressure mainly from the external market for the export of mineral resources and domestic market demands, especially for steel mills, also located mostly in Minas Gerais (Oliveira, 2013; IBRAM, 2021a, 2021b).

The high increase in Mining, especially after 2012, observed by Rezende (2016) and emphasized in this research, is also related to changes in the Forest Code made in 2012. Until that year, the main Environmental Laws in Brazil related to this activity were the Forestry Code and the Mining Code, which imposed restrictions on the use and exploitation of natural resources by private landowners and companies. Although, with private interests of politicians and big businessmen, these Codes were and have been changed, resulting in major threats to the environment (Rezende, 2016; Diniz et al. 2014; Vieira et al. 2018; Mueller, 2018; Milanez et al. 2019).

Thus, becoming even more evident when evaluating the history of intense and recurrent changes in the Brazilian Environmental Legislation at the Federal level, which resulted in great risk and generated eminent obstacles for the conservation and maintenance of Forest areas in the whole country. These facts were pointed out in the studies of Abessa et al. (2019), Mercure et al. (2019), Bragagnolo et al. (2017), and Milanez et al. (2019). Furthermore, the recent environmental crimes near the QF region, as shown in Rotta et al. (2020) and Cionek et al. (2019),

emphasize that there are still obstacles to ensuring the effectiveness of safety compliance for society and the environment. In this way, the environmental-economic paradox is once more expressed, as all the increase in Forest class, observed from 1985 to 2018 in the QF, may be threatened soon, since Mining and Farming are directly dependent on decisions taken in Environmental Legislation and receive more attention, leaving Forests only at the "mercy" of these defined impediments.

According to future projections of Forest metrics, the increase in patch shape values (SHAPE), combined with the increase in total area (CA) and decrease in the core area (CAI_MN), culminating in a worrying scenario from the perspective of the ecology of organisms dependent on these natural habitats. This shows that, even with larger areas, irregularly shaped fragments will suffer a greater incidence of edge effects since core areas tend to decrease. In this way, abiotic factors increasingly move into the interior of these patches, causing direct and indirect damage to the plant species (Zambrano et al., 2020). In addition, this decrease in the usable area required by organisms reflects mainly on the maintenance of the population of animals sensitive to habitat loss (Keinath et al., 2017), beyond affecting evolutionary characteristics because of density-dependent phenomena (Legrand et al., 2017). Furthermore, the tendency to decrease the aggregation of these patches also confers possible damage to biodiversity, especially plant biodiversity, since the more isolated a fragment is, the greater the consequences for the dispersal of flora, which affects the gene flow between patches, making the landscape more sensitive to changes in its structure (Cote et al., 2017).

Added to this, the QF region showed increasing heterogeneity in its composition, that is, the great structural diversity of the landscape, not having a predominant type of land use and occupation due to the area's exploitative history. From an ecological point of view, these results are worrying in two senses: 1. the natural vegetation does not exert predominance over the others; 2. the continuous fragmentation process of the forests can lead to a homogeneous landscape, with only anthropic use classes as predominant. That said, as highlighted by Plexida et al. (2014), the intensification of anthropic activities, especially in high-altitude regions, as is the case of the QF, result in increasingly heterogeneous landscapes. In general, these results are relevant, especially to future recovery practices of degraded habitats, because knowing the evolution of landscape heterogeneity is essential for reintroduction processes and species conservation. (Caughlin et al. 2019).

Therefore, the need for sustainability actions, pre and post-exploitation recovery techniques, elaboration, and maintenance of UCs, associated with the pressure of Farming and advancement of Non-Vegetated Areas. Those are some of the reasons that require greater rigor in monitoring the landscape integrated into the existing industrial driving force (Okado and Quinelli, 2016; Florkowska and Bryt-Nitarska, 2018) as occurs in the QF region, which has extensive areas of intense Mining and Farming, and the urbanization process extremely advancing over the region's Forests. Consequently, studies that benefit the development of increasingly sustainable Mining have never been so current and urgent, as Monteiro et al. (2021) discussed. For that reason, it is important to combine exploration and sustainability with a Green Economy as the main focus of this research. Thus, sought to highlight the negative and positive points achieved during more than 30 years of exploration in the QF and contribute to the decision-making to ensure a balanced future between Economy and Environment.

Moreover, when considering all the Mining events for the country in recent years, the need to maintain ongoing studies to assess and monitor the environmental impacts caused mainly by mining companies is evident. Thus, assisting in improving conservation practices and, consequently, in the valuation of mineral resources exploited in these regions. In any case, the QF region, during the period evaluated, presents interesting environmental conditions from the ecological point of view. However, due to the Legal and Environmental factors that currently occur, its maintenance for the near future also depends on the pressure exerted on the large producing companies to avoid more severe damage to the landscape. Thus, it is necessary to ensure that this historical, cultural, and economic heritage is maintained for future generations, which can only be achieved by forming alliances from the Public Power, Private, and Population Representatives, aligning the interests.

Although it is evident, mineral extraction associated with Farming in land use in QF has caused intense and extensive influence on the landscape. In addition, even with the adoption of conservationist practices, it is still necessary to know the patterns assumed by these interferences to help in the decision-making of several entities involved in territorial planning and environmental conservation in this important portion of the State of Minas Gerais for the country and the world. In this way, verifying the influence and impact of these environmental exploration activities on the landscape configuration becomes an interesting and powerful tool for pointing out the environmental consequences. This is an essential attribute for the Public Agency's short- and

long-term planning of environmental control and licensing, especially for the mining companies inserted in the region studied.

4. Conclusion

The future prediction procedure was effective but required attention since the QF is an area of great influence in and of the Brazilian Economy. Thus, its growth also depends on the annual economic behavior of the country and the world and the current laws due to its importance and social, environmental, and economic interference. Furthermore, from an ecological point of view, the projections showed worrying results for the maintenance of biodiversity, mainly related to the disaggregation of the remaining forest fragments in the region.

Preserving the Forest zones, either through UCs, recovery areas, or environmental education activities, favored the increase of this class in the evaluated period. Therefore, this can be an effective measure to avoid future damage if the methods and goals established by governments and companies are improved. However, the mining companies play a fundamental role in this maintenance. Thus, they must invest in more and more intelligent methods for complying with the norms of environmental licensing, the concession of new mines, and other conservationist practices to maintain the forests in the QF region since it is the land-use class with the greatest contribution to the increase and expansion of Mining.

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