10.15446/rcdg.v28n1.67506

Cuadernos de Geografía: Revista Colombiana de Geografía

Landscape Fragmentation around Ferruginous Caves of the Iron Quadrangle, Minas Gerais, Brazil

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Abstract

The aim of this article is to analyse the landscape fragmentation around ferruginous caves in the Iron Quadrangle (Minas Gerais, Brazil) and the conditions of environmental stability of the caves inserted in vegetal remnants under edge effects caused by anthropic activities. The methodology applied involved the implementation of three different landscape metrics to stablish the total area of patches, the area of the patches under edge effects (core area), and the distance from the nearest neighbour. The measurements were calculated considering classes of vegetal coverage (herbaceous, shrub, and arboreal vegetation) and then processed and combined by using map algebra to obtain the fragmentation degree, which was classified into three classes: high, moderate, and low. Results reveal that 62.88% of the vegetation coverage of the study area presents a low degree of fragmentation. Among the caves under edge effects, 15% obtained negative indices of environmental stability. Although most of the analysed caves are located in areas with a low degree of fragmentation, the proximity of anthropized areas and the risk they represent for the speleological heritage reinforce the need to create strategies focused on the conservation of the caves.

Keywords: ferruginous cave, iron geosystems, Iron Quadrangle, landscape metrics, speleological heritage.

Featured ideas: research article on the results of research carried out regarding the composition and configuration of the landscape surrounding ferruginous caves located in the Iron Quadrangle, in the state of Minas Gerais, Brazil.

RECEIVED: 5 SEPTEMBER 2017. | EVALUATED: 5 FEBRUARY 2018. | ACCEPTED: 5 MARCH 2018.

HOW TO CITE THIS ARTICLE

Gomes, Mauro, Úrsula de Azevedo Ruchkys, Rodrigo Lopes Ferreira, y Fernando Figueiredo Goulart. 2019. "Landscape Fragmentation around Ferruginous Caves of the Iron Quadrangle, Minas Gerais, Brazil." *Cuadernos de Geografía: Revista Colombiana de Geografía* 28 (1): 89-101. doi: 10.15446/rcdg.v28n1.67506.

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Fragmentación del paisaje alrededor de las cuevas ferruginosas del Cuadrilátero Ferrífero de Minas Gerais, Brasil

Resumen

El objetivo de este artículo es analizar la fragmentación del paisaje alrededor de las cuevas ferruginosas del Cuadrilátero Ferrífero (Minas Gerais, Brasil), así como las condiciones de estabilidad ambiental de las cuevas ubicadas en remanentes vegetales sujetos al efecto de borde causado por actividades antrópicas. La metodología aplicada involucró la implementación de tres diferentes métricas de paisaje para establecer el área total de parches, el área de los parches bajo efectos de borde (área principal) y la distancia del vecino más cercano. Las medidas se calcularon con base en clases de cobertura vegetal (vegetación herbácea, arbustiva y arbórea) y luego se procesaron y combinaron a través de álgebra de mapas para obtener el grado de fragmentación, que se clasificó en tres clases: alto, moderado y bajo. Los resultados muestran que el 62.88 % de la cobertura vegetal del área estudiada presenta un grado de fragmentación bajo. Entre las cuevas con efectos de borde, el 15% mostró índices negativos de estabilidad ambiental. Aunque la mayoría de las cuevas analizadas están ubicadas en áreas con grado de fragmentación bajo, la cercanía de áreas antropizadas y el riesgo que representan para el patrimonio espeleológico reconfirman la necesidad de crear estrategias enfocadas en la conservación de las cuevas.

Palabras clave: cueva ferruginosa, geosistemas ferruginosos, Cuadrilátero Ferrífero, métricas de paisaje, patrimonio espeleológico.

A fragmentação da paisagem em torno das cavernas ferruginosas do Quadrilátero Ferrífero de Minas Gerais, Brasil

Resumo

O objetivo deste artigo é analisar a fragmentação da paisagem em torno das cavernas ferruginosas do Quadrilátero Ferrífero (Minas Gerais, Brasil), bem como as condições de estabilidade ambiental das cavernas localizadas em remanescentes vegetais sujeitos ao efeito de borda causado por atividades antrópicas. A metodologia aplicada envolveu a implementação de três diferentes métricas de paisagem para determinar a área total das manchas, a área das manchas sob os efeitos de borda (área core) e a distância do vizinho mais próximo. As medidas foram calculadas com base nas classes de cobertura vegetal (vegetação herbácea, arbustiva e arbórea) e posteriormente processadas e combinadas por meio de álgebra de mapas para obter o grau de fragmentação que foi classificado em três classes: alto, moderado e baixo. Os resultados mostraram que 62,88% da cobertura vegetal da área estudada apresenta um baixo grau de fragmentação. Entre as cavernas com efeito de borda, 15% apresentam índices negativos de estabilidade ambiental. Embora a maioria das cavernas analisadas estejam localizadas em áreas com baixo grau de fragmentação, a proximidade de áreas antrópicas e o risco que representa para o patrimônio espeleológico confirmam a necessidade de criar estratégias focadas na sua conservação.

Palavras-chave: caverna ferruginosa, geossistemas ferruginosos, Quadrilátero Ferrífero, métricas da paisagem, patrimônio espeleológico.

Introduction

Caves are part of the landscape and as such, they are subject to changes imposed by natural and anthropic factors occurring in their surroundings. The evolution of landscapes where caves are inserted and the impact of such changes on the subterranean environment have motivated the development of several research projects, especially in karstic areas where the impacts are more noticeable than in other lithologies (Klimchouk and Andrejchuk 1996). Jiménez-Sánchez et al. (2008) addressed this issue in a study regarding groundwater contamination by agricultural activities and urbanization. The human influence on groundwater quality was also researched by De Waele and Follesa (2003) and impacts caused by agriculture were studied in several other parts of the world (Akdim and Amyay 1999; Balák et al. 1999; Bánány-Kevei 1999; Burri, Castiglioni and Sauro 1999; Gillieson and Thurgate 1999; Ginés 1999; Kohler, Pinto and de Abreu 1999). However, studies relating the evolution of landscape in iron geosystems and the consequences for the speleological heritage are scarce.

In Brazil, approximately 68% of the speleological heritage is composed by limestone caves. However, data from research and prospection in other lithologies with potential for occurrence of caves has been increasing, especially in the last few years, for regions with ferruginous lithology (Cavalcanti et al. 2013).

Until the beginning of the 21st century, little was known in Brazil about ferruginous caves (Piló, Coelho and Reino 2015), but given the increasing world demand for iron and the ensuing need for research regarding the processes of environmental licensing, there was a substantial improvement in speleological prospection. This situation has revealed that ferruginous lithologies, despite being spatially restricted, present a high potential for occurrence of caves. The records identified in such environments substantially increased since 2009, from about 200 to 3000 records according to the main speleological databases of the country (Piló, Coelho and Reino 2015). Currently, caves found in ferruginous systems already represent 20% of the Brazilian speleological heritage (Cavalcanti et al. 2013).

Iron geosystems are spatial units predominantly composed of ferruginous lithotypes that in Brazil are restricted to few regions outside the state of Minas Gerais (Iron Quadrangle, West border of Serra do Espinhaço and Rio Peixe Bravo Valley), Pará (Serra de Carajás), Bahia (Rio São Francisco Valley) and Mato Grosso do Sul (Urucum plateuau). In the Iron Quadrangle, the occurrence of such ferruginous lithotypes is distributed in Archaean (Super-group Rio das Velhas), Proterozoic (Super-group Minas) and Cenozoic (Formation Chapada de Canga) (Ruchkys 2015).

Such geosystems shelter singular caves with small dimensions, mostly developed under surface deposits of breccia rich in hematite cemented by limonite (Simmons 1963). These caves present high species richness when compared to those associated with other lithologies (Souza-Silva, Martins and Ferreira 2011), are generally located close to the surface, and are made up of a single chamber and appendages which taper into small channels (Piló, Coelho and Reino 2015). Such canaliculi represent one of the main characteristics of this type of cavity, which form an extensive network of interstitial spaces interconnecting macro, meso and microcaves (Ferreira 2005).

In these singular environments, the balance of cave communities depends on attributes intrinsic to the caves such as light conditions, temperature and moisture to guarantee their environmental stability. Such parameters are strongly influenced by the general characteristics of entrances and their relation to the dimensions of caves (Bento et al. 2016; Ferreira 2004; Pellegrini et al. 2016). Biotic factors are also responsible for such balance. The trophic chain of such environments is mainly supported by the consumption of roots from external trees and shrubs, which develop through interstices in the rock and reach the cave chambers (Ferreira 2005; Ferreira, de Oliveira and Silva 2015). Besides the roots, guano and organic matter deposits represent important food sources for the cave fauna, which are carried into the caves by the wind or water (Ferreira, de Oliveira and Silva2015; Souza-Silva, Ferreira and Martins 2011). The composition of such sources of energetic supply highlights the important role of vegetal cover surrounding the ferruginous caves regarding the maintenance of the subterranean environment.

Changes in the landscape and consequent impacts on the vegetal cover caused by the expansion of urban centers and mainly the high concentration of mining enterprises in the region of the Iron Quadrangle, as well as the projections regarding the evolution of these landscapes (Oliveira 2012; Sonter et al. 2014; Sonter et al. 2014; Oliveira 2015) stand out in this region due to the accelerated degradation of natural areas around the caves. This scenario motivated the development of this research project, aimed at analyzing the fragmentation of vegetal cover around ferruginous caves and the conditions of environmental stability of caves inserted in vegetal remnants under edge effects caused by anthropic activities.

Methods

Study area

The study area (figure 1) is located on Southeastern Brazil, in the western portion of the Iron Quadrangle, state of Minas Gerais, including 12 municipalities and approximately 53,000 ha. The region is located in the transition between the biomes Cerrado (Brazilian savannah) and Atlantic Forest, two hotspots for the conservation of the world's biodiversity (Myers et al. 2000). Approximately 67% of the territory of the study area is covered by native forest, while the rest is occupied by anthropic activities, notably those related to mining. The boundaries were defined considering the speleological districts of Curral-Rola Moça and Serra da Moeda (Ruchkys, Pereira and Pereira 2015), for which there are 235 caves recorded (CECAV 2016), all inserted in ferruginous formations.

Methodology

The study of landscape fragmentation was conducted in GIS environment, considering the map of vegetal cover and land use drawn from Landsat image 218/074 dated 08/31/2015. In this map, the vegetal cover was classified considering only the size of species, which were characterized into herbaceous, shrub, and arboreal vegetation. The anthropic classes were represented by mining, urban, forestry, pasture areas, and exposed soil.

Landscape metrics regarding the total area of patches, the area of patches considering the edge effect (core area) and distance from the nearest neighbor, were extracted

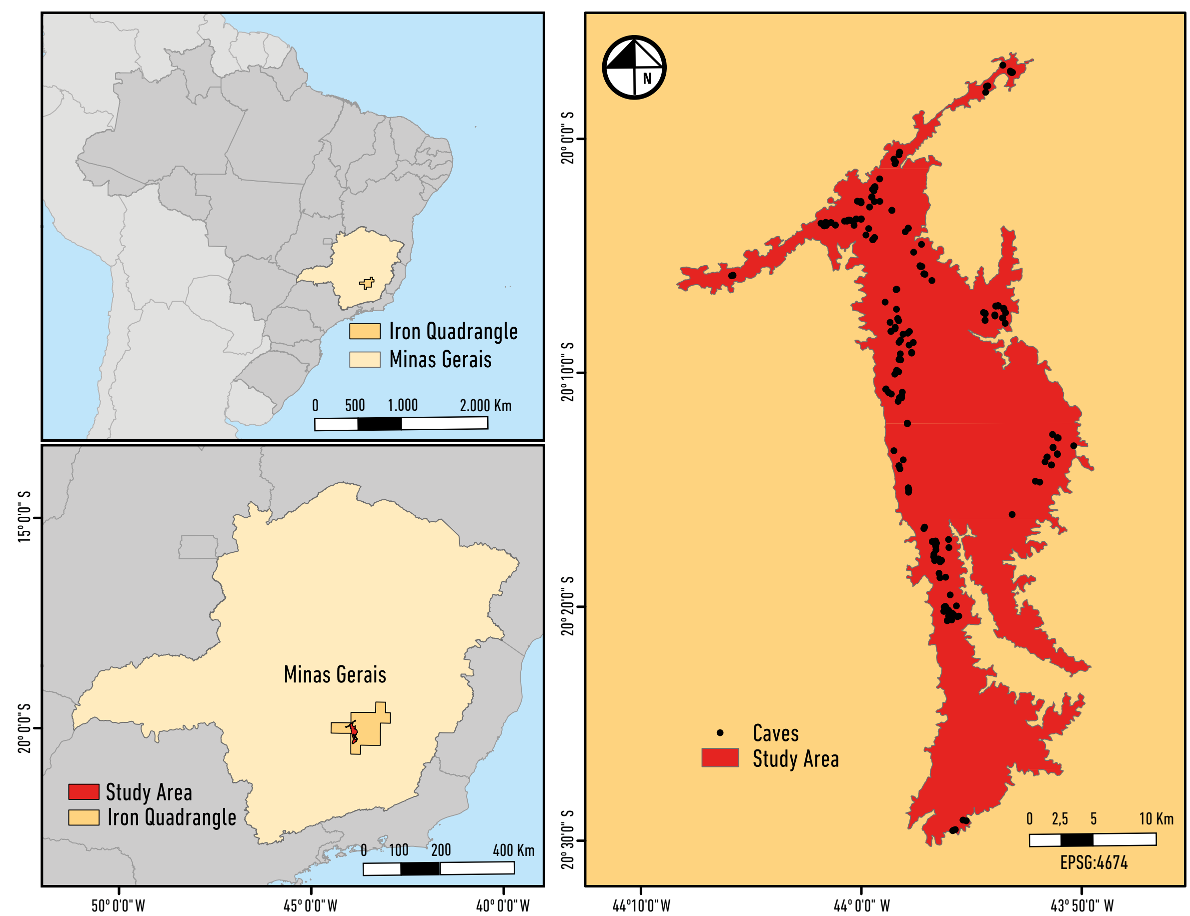

Figure 1. Location of study area in the Iron Quadrangle, central region of the state of Minas Gerais (MG), Brazil.
Source: adapted from Gomes 2017, 31; Lobato et al. 2005; IBGE/DGC 2014.

from classes of vegetal cover. These three elements were combined in map algebra to obtain the fragmentation degree divided into three classes (high, moderate, and low) according to the proposal of Santos and Machado (2015).

The map algebra was processed from the following equation 1:

Equation 1.

$$F = AREA + CORE + ENN\_MN$$

F: fragmentation degree.
AREA: area of fragments.
CORE: core area.
ENN_MN: distance from the nearest neighbor.

The distance of 50 m was considered for the definition of edge to calculate the core area.

The result of such combination produced the Synthesis Map of Fragmentation Degree of Vegetal Cover (SMFDVC). The coordinates of the 235 caves were plotted on the SMFDVC in order to calculate the index of environmental stability of caves involved by the vegetal cover under the influence of edge effects.

The Index of Environmental Stability (IES) proposed by Ferreira (2004) was used to determine the environmental stability of the caves (Bento et al. 2016; Ferreira 2004; Pellegrini et al. 2016). In the case of caves with only one entrance, this indicator was obtained through equation 2:

Equation 2.

$$IES = \ln (ET / EE)$$

IES: Index of Environmental Stability.
ET: total extension of the cavity.
EE: extension of the cavity entrance.

For caves with more than one entrance the following equation was used:

Equation 3.

$$IES = \ln ((ET/\Sigma EE) / (((NE * DEE))/ET))$$

IES: Index of Environmental Stability.
ET: total extension of the cavity.
ΣEE: Sum of the extensions of the cavity entrances.
NE: number of entrances.
DEE: mean distance between the entrances taken from one reference entrance.

The speleometric data used for the calculation of IES were extracted from topographic maps or were verified *in loco* during field expeditions to validate the map of vegetal cover and land use.

Results

The map produced from the combination of three landscape metrics (figure 2) presents the fragmentation of vegetal cover of the study area considering the dimensions of patches, edge effects, and also connectivity among patches of the same class (herbaceous, shrub, or arboreal). The map areas classified with high degree of fragmentation refer to patches with the smallest total area, smallest core area, and larger distances among patches, while those classified with low degree represent the largest areas (total and core) and the shortest distances among patches of the same class.

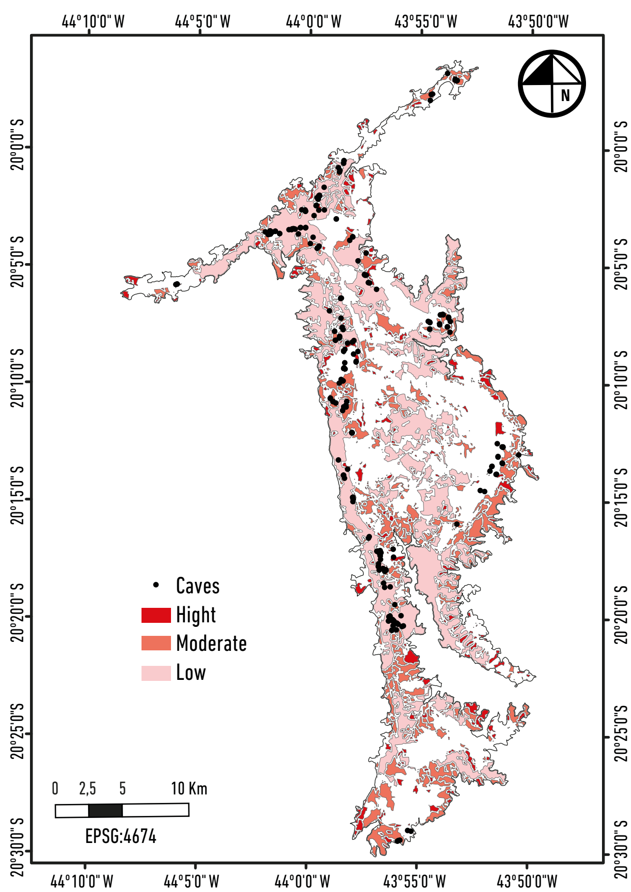

Figure 2. Synthesis map of the fragility degree of the vegetal cover. Source: Gomes 2017, 74.

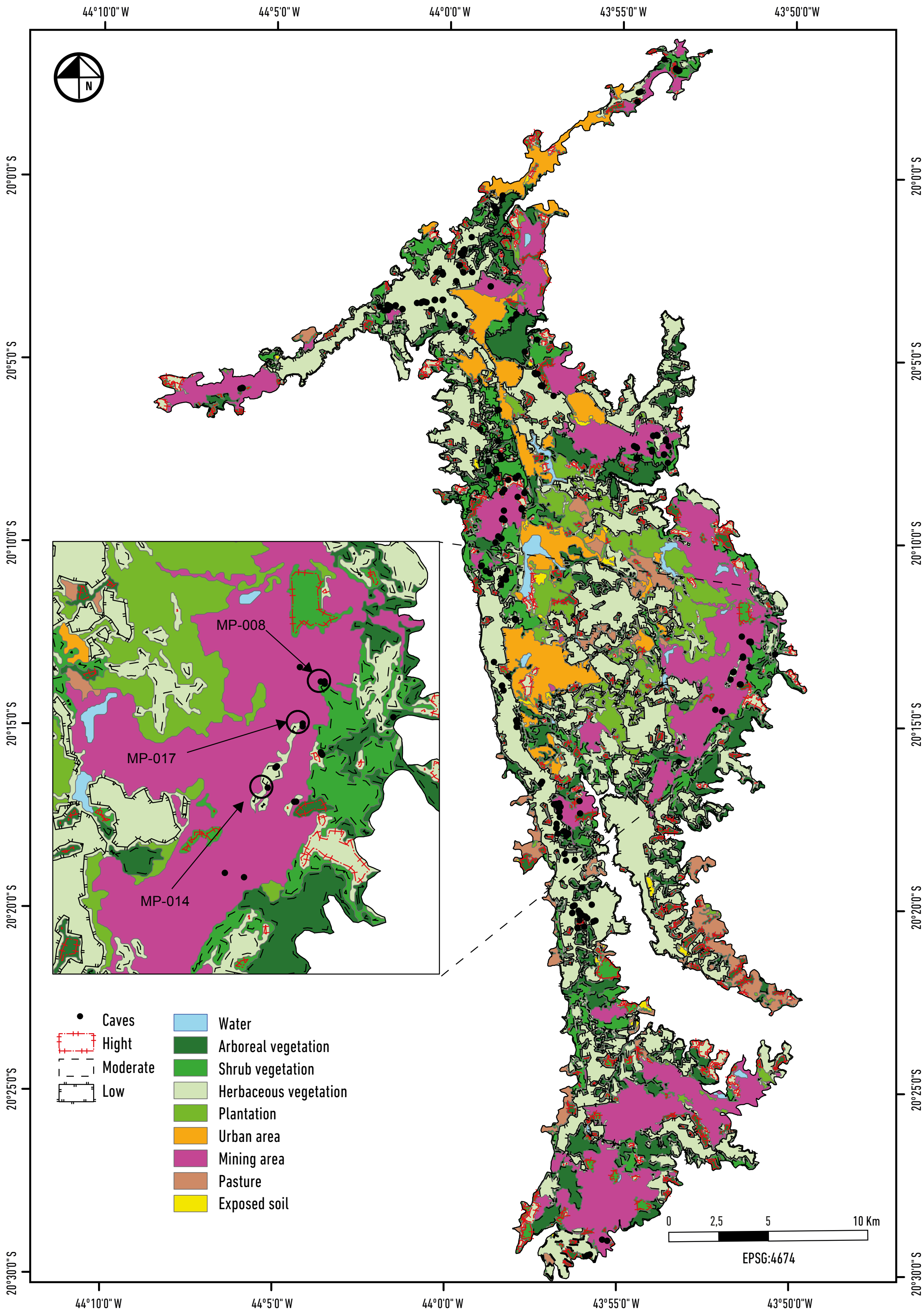

Figure 3. SMFDVC indicating the relations between the degree of fragmentation and the different classes of vegetation cover and land use. Detail shows the location of caves MP-008, MP-014 and MP-017.
Source: Gomes 2017, 75.

Table 1 presents data related to the number of patches, mean area, and total area of patches of vegetal cover according to the degree of fragmentation.

Table 1. Classification of patches of vegetal cover considering the Synthesis Map of Fragmentation Degree

Degree	N.patches	Mean(ha)	Total (ha)
High	648	2.81	1,822
Moderate	843	7.40	6,237
Low	230	59.36	13,651

Source: Gomes 2017, 73.

Although the data revealed a high number of highly or moderately fragmented patches, 62.88% of the vegetal cover presented a low degree of fragmentation, 28.73% presented a moderate degree, and 8.40%, a high degree, with respect to the total area.

The SMFDVC was overlaid on the map of vegetal cover and land use to illustrate the anthropic interference in the landscape. Figure 3 presents such situation in which it is possible to verify that moderately and highly fragmented areas are predominantly found around anthropized areas (mining, forestry, and urban areas), thus indicating a possible influence of these activities on the fragmentation.

Overlaying the 235 caves on the SMFDVC allowed the classification of caves according to the fragmentation degree of the surrounding area. Figure 4 presents such result considering the areas without significant vegetal cover and also regions where the vegetal cover, despite existing, is more susceptible to the edge effect.

It is possible to identify three distinct groups of caves. The first includes 112 caves situated within the vegetal cover, which despite presenting different degrees of fragmentation, are less subject to the edge effect. Caves VL-29 and VL-30 are in this group, where the troglobitic species Collembola *Troglobius ferroicus* occurs (Zeppelini, da Silva and Palacios-Vargas 2014), and also cavity MS-19 for which the troglobitic spider *Brasilomma enigmatica* is recorded (Brescovit et al. 2012), both in areas classified with low degree of fragmentation.

In the second group there are 36 caves located in highly impacted, anthropized areas without significant vegetal cover. The suppression of a large number of these caves was already authorized by the competent organs (Ribeiro 2015) and the others are in a critical situation since both the cave and surroundings have been subject to irreversible impacts.

It is important to highlight the presence of caves MP-008, a unique habitat known for the rare and endemic troglobitic *Ferricixius davidi* (Hoch and Ferreira 2012), considered one of the planthoppers most modified to the subterranean lifestyle, and also MP-014 and MP-017, with records of the troglobitic harvestman *Gonycranaus pluto* (Bragagnolo, Hara and Pinto-da-Rocha 2015). The location of such caves may be observed in figure 3, in which it is possible to notice that, despite their being close to patches with vegetal cover with moderate degree of fragmentation, they are in areas significantly altered by mining activities.

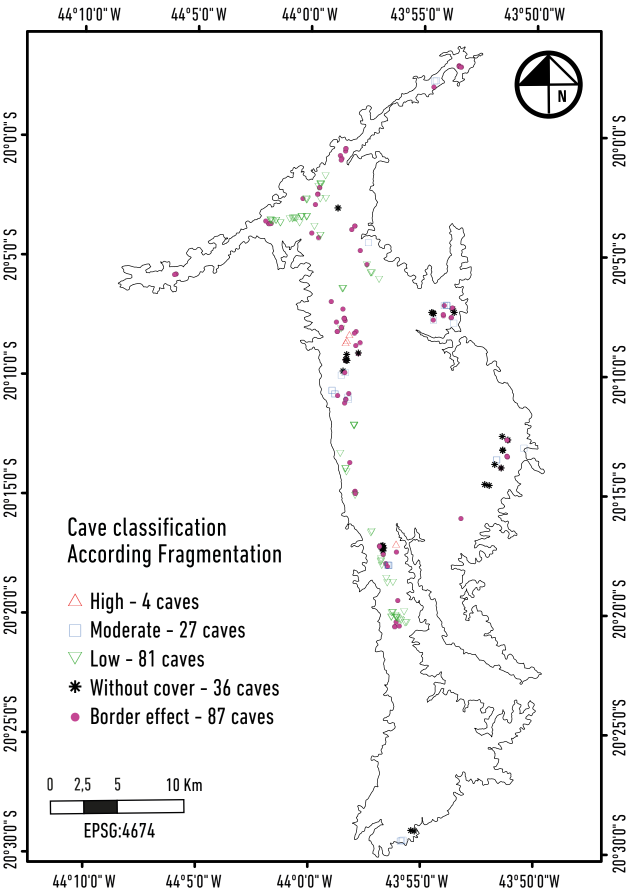

Figure 4. Synthesis map of cave classification according fragmentation of vegetal cover.

The third group includes 87 caves inserted in the most peripheral region of the vegetation patches which, therefore, are susceptible to the edge effect. For this reason, this group of caves was chosen for the application of the Index of Environmental Stability (IES). The analysis of such index was also conducted considering the type of vegetal cover where the cavity is inserted, the type of nearest anthropic activity, and the respective distance. In this group, 51 caves (58% of the total) presented positive values for that index, thus granting them the status of high environmental stability. Moreover, in this group, the situation of caves presented in table 2 stands out in terms of their distance with respect to anthropized areas.

Table 2. Caves with the greatest environmental stability inserted in patches with vegetal cover subject to the edge effect

Cave	Cover	IES	Activity	Dist (m)
VL-07	Herbaceous	2.11	Mining	15.06
SM-17	Shrub	1.98	Mining	17.12
MS-17	Herbaceous	1.85	Mining	4.95
SM-16	Herbaceous	1.56	Mining	1.57
VL-43	Arboreal	1.44	Mining	7.83
RM-42	Arboreal	1.22	Urban patch	12.3
VL-53	Herbaceous	1.03	Mining	3.22

Source: Gomes 2017, 76.

Although they are still inserted in fragments with vegetal cover, the environmental stability of such caves may be compromised due to their great proximity to impacted areas. Figure 5 shows the location of cave VL-53, inserted in a herbaceous patch close a mining plant.

Table 3 presents the relation of the 13 caves that presented negative values for such index, thus representing the caves with lowest environmental stability.

Also presented in table 3 is the situation of caves closer to anthropized areas, which stand out for the same reason: the fact that their environmental stability is compromised.

Table 3. Caves with the lowest environmental stability inserted in patches of vegetal cover subject to edge effects

Cave	Cover	IES	Activity	Dist (m)
SM-24	Herbaceous	-1.21	Urban patch	1,580.45
RM-11	Herbaceous	-0.86	Mining	89.95
RM-23	Shrub	-0.50	Urban patch	478.80
RM-12	Herbaceous	-0.46	Mining	52.17
RM-13	Herbaceous	-0.38	Mining	24.59
RM-05	Herbaceous	-0.28	Mining	382.40
VL-45	Arboreal	-0.22	Pasture	997.23
SM-18	Shrub	-0,18	Mining	26.52
MS-01	Shrub	-0,07	Plantation	717.88
RM-37	Arboreal	-0,06	Urban patch	112.72
SM-02	Shrub	-0,03	Mining	885.84
MS-05	Shrub	-0,01	Mining	531.63
RM-31	Herbaceous	-0,01	Mining	1,250.96

Source: Gomes 2017, 76.

Figure 6 shows the location of cave SM-24 in a herbaceous/arboreal patch, approximately 1,500 meters from an urban patch and 1,700 meters from a mining plant (in the background).

It was not possible to calculate the IES for the 23 remaining caves due to restrictions regarding entrance to mining properties and to the inexistence or unavailability of topographic maps.

Discussion

In a fragmented landscape, both the heterogeneity of the habitat and the distance among feasible habitats have a strong relation to the composition and richness of species that inhabit the fragments (Honnay et al. 2003). The process of habitat loss and fragmentation constitutes the most important threat for mammals, birds, and plants worldwide, thus causing the decrease of quality and availability of habitat, as well as the loss of landscape connectivity (Martínez, Ramil and Chuvieco 2010).

Studies related to alterations in the landscape and their impacts on the subterranean environments are still scarce and are predominantly related to karstic areas (Akdim and Amyay 1999; Balák, Stefka and Bosák 1999; Bánány-Kevei 1999; Burri, Castiglioni and Sauro 1999; Gillieson and Thurgate 1999; Ginés 1999; Jiménez-Sánchez et al. 2008; Kohler, Pinto and Abreu 1999; de Waele and Follesa 2003), dealing with analysis of the impacts caused by agriculture and groundwater contamination. There is little scientific production that connects the external landscape with cave biodiversity and that discusses alterations in the availability, composition, and abundance of allochthonous trophic resources and their influence on the balance of such fragile ecosystems (Pellegrini et al. 2016; Phelps, Labonite and Kington 2016).

Discussions based on data presented in this article considered mainly the fragmentation of vegetal cover caused by the removal of vegetation due to anthropic actions. In this sense, it is important to highlight that the fragmentation comprises both those areas where such phenomena occur naturally due to factors like topography, climate, and soil, and those where fragmentation may be associated with anthropic actions due to removal of vegetation, for instance, to install mining or urban infrastructure, or for pastures or eucalypt plantations.

The analysis of SMFDVC indicated that most of the vegetal cover of the study area presented a good status

Figure 5. Location of cave VL-53, close a mining plant.
Author's photograph, march 2017.

Figure 6. Location of cave sm-24 in a herbaceous/arboreal patch.
Author's photograph, February 2017.

of conservation in terms of the low degree of fragmentation. Both data obtained through remote sensing and consultation of databases and that from personal observation in the field revealed that a large part of the remnants of vegetal cover is located on properties of mining companies involved in licensing processes that may originate future mining concessions. The good conservation status of these areas may be a consequence of actions imposed by the current environmental legislation on such enterprises as compensatory measures to activities of mining extraction, which, in theory, would guarantee the conservation of these areas against degradation caused by mining. However, the increasing demand for iron ore, a determining factor for the increase of environmental degradation in this region, points to a worsening of the conflict between environmental conservation and economic development in the upcoming years.

In relation to the speleological heritage, the fact that 52% of caves of the study area (36 without vegetal cover and 87 under edge effects) are directly threatened by anthropic actions is cause for concern, particularly if we take into account the scarce scientific knowledge on the subterranean ecosystem of this region. The analysis of IES for caves subject to edge effects reveals that even considering that many of them presented positive values of this index, the caves and their surroundings are located a few meters away from anthropized areas.

The influence of alterations of the surrounding landscape on the cave communities may be even more critical for caves with lower environmental stability (table 4). It is important to highlight that 53% of this group is located within the Parque Estadual da Serra do Rola Moça, a conservation unit of comprehensive protection. In this context, there are four caves situated less than 100 m from mining activities, and the influence area of three of them, RM-11, RM-12 and RM-13 (figure 7) was already affected by mining activities developed near the park.

Table 4. Caves with the lowest environmental stability inserted in patches of vegetal cover subject to border effect

Cave	Cover	IES	Activity	Dist (m)
SM-24	Herbaceous	-1.21	Urban patch	1,580.45
RM-11	Herbaceous	-0.86	Mining	89.95
RM-23	Shrub	-0.50	Urban patch	478.80
RM-12	Herbaceous	-0.46	Mining	52.17
RM-13	Herbaceous	-0.38	Mining	24.59
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SM-02	Shrub	-0,03	Mining	885.84
MS-05	Shrub	-0,01	Mining	531.63
RM-31	Herbaceous	-0,01	Mining	1,250.96

Source: Gomes 2017, 76.

In this particular case, mining extraction was already going on when the park was created in 1994; however, the activity was only suspended in 2001, thus leaving tailings piles as legacy. Currently, the pressure to resume mineral production in the region is strong and proposals to that effect exist since 2008 (Tonidandel 2011). This scenario illustrates the pressure suffered by protected areas close to conflicting places in terms of mineral production, as emphasized by Durán, Rauch and Gaston (2013). Regarding ferruginous caves, more specifically, Carmo, de Campos and Kamino (2015) demonstrated that the mere fact that a cave is situated in a conservation unit does not guarantee efficient measures to protect the speleological heritage.

This situation shows the fragility of this type of cavity and surrounding areas of the region. The ecological synergy and effect that anthropic actions exert over the speleological heritage still require more studies, mainly regarding the area of influence of caves. In this sense, it is important to highlight that the definition of "area of influence of caves" is still incipient in Brazil (CECAV 2013). The 250 m radius, considering the projection in surface of the linear development of the cavity, recommended by the legislation (IBAMA 1990) is considered precarious both from the conservation and economic development points of view (Auler and Piló 2015; Dutra, Lott and Brandi 2015).

Final considerations

This study sought to call attention to the need of better understanding the composition of vegetal cover around caves, considering its role in providing support to the cave communities, and the consequences of alterations in such cover for the ecological stability of the subterranean environment. Therefore, the objective was to provide support for future research and contribute to defining priority actions regarding the environmental stability of caves and the influence of the main types of impacts to which they are subject due to alterations in the surroundings.

It is important to highlight the scarcity of quantitative and qualitative evaluations that objectively point out the losses and environmental damages occurred in the influence areas of caves located in iron geosystems. Funding to conduct research in this region is still incipient since most of the studies are associated with processes of environmental licensing, without efforts being made to go beyond the licensing scope. However, despite all the obstacles, new species have been recorded in these environments, some of them extremely rare and strongly threatened. This reinforces even more the need for speleological studies, since the current model of environmental licensing is tolerant of the occurrence of negative impacts and allows for the suppression of

Figure 7. Speleologist situated above cave rm-13, close to a mining plant. Author's photograph, January 2017.

caves, thus providing several possibilities to change the landscape and consequently the biodiversity patterns.

Acknowledgments

We would like to express our thanks to the National Institute of Space Research (INPE), which provided the Landsat images used to draw the map of vegetal cover and land use, through the Image Generation Division of Cachoeira Paulista/SP; to the National Center for Research and Conservation of Caves (ICMBio/CECAV) to the National Council of Technological and Scientific Development (CNPq - grant 304682/2014-4); and to the Foundation for Research Support of Minas Gerais (FAPEMIG) (FAPEMIG - grant APQ-02956) for the research grant.

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