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Mining in Carbonate Rocks in the Metropolitan Region of Curitiba, PR: Challenges for the Preservation of Karst and Speleological Heritage

A mineração em Rochas Carbonáticas na Região Metropolitana de Curitiba- PR: Desafios para a Preservação do Patrimônio Cárstico e Espeleológico

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Abstract

Carbonate rocks are the lithotypes with the highest volume of exploitation and financial profitability in the Metropolitan Region of Curitiba (RMC), representing the most important mineral source for the cement industry, aggregates in construction, soil acidity correction, as well as housing the Karst Aquifer of the RMC, ornamental rock mines, and providing inputs for the manufacturing industry. However, mining activity, carried out in open-pit operations through the dismantling of rock masses usually using explosives, directly impacts the karst landscape and regional speleological heritage, especially the dozens of caves occurring in the region. Therefore, considering the irreversible nature of the environmental impacts resulting from mining and the lack of continuous monitoring of mined areas, remote sensing data, official mining data, and records of environmental damage were used to identify the growth of carbonate rock mining and its impacts on regional karst and speleological heritage. Specifically, the following data were used: records from the National Mining Agency (ANM), historical records from the Paraná Speleological Studies Group (GEEP-Açungui), and primarily, 1980-2022 land use and land cover change dataset derived from Landsat 5, 7, and 8 series of images. The increase in the land use classified as "mining" between 1980 and 2022, the annual increase in revenue from the Financial Compensation for Mineral Exploration, and the presence of dozens of caves in areas with active mining processes allowed for identifying that the growth of mining activity in carbonate rocks constitutes the greatest challenge to preserving the karst systems of the RMC.

Keywords:

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Caves, Mineral Exploitation, Remote Sensing, Google Earth Engine.

Resumo

As rochas carbonáticas são os litotipos com maior volume de explotação e rentabilidade financeira na Região Metropolitana de Curitiba (RMC), representando a mais importante fonte mineral para a indústria cimentícia, agregados para a construção civil, correção do solo, insumos para a indústria de transformação, além de abrigar o Aquífero Karst da RMC. Porém, a atividade minerária, realizada a céu aberto com o desmonte dos maciços rochosos com o uso de explosivos, impacta diretamente a paisagem cárstica e o patrimônio cárstico regional, notadamente as dezenas de cavernas ocorrentes na região. Assim, considerando a natureza irreversível dos impactos ambientais resultantes da mineração e a ausência de um monitoramento contínuo dessas áreas, utilizou-se dados de sensoriamento remoto, dados minerários oficiais e registros de danos ambientais para identificar o crescimento da mineração de rochas carbonáticas e os impactos sobre o patrimônio espeleológico regional. Os dados da Agência Nacional de Mineração (ANM), os registros históricos do Grupo de Estudos Espeleológicos do Paraná (GEEP-Açungui) e, principalmente, o mapeamento das mudanças de uso da terra a partir da análise de imagens das séries Landsat 5, 7 e 8, foram os dados e informações considerados na análise. O aumento da área com uso e cobertura da terra classificada como "mineração" entre 1980 e 2022, o incremento anual na arrecadação da Compensação Financeira pela Exploração Mineral (CFEM) e a presença de dezenas de cavernas em áreas com processos minerários ativos permitiram identificar que a mineração em rochas carbonáticas constitui o maior desafio à preservação dos sistemas cársticos da RMC.

Palavras-Chave:
Cavernas, Explotação Mineral, Sensoriamento Remoto, Google Earth Engine.

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I. INTRODUCTION

Mining exploration of carbonate rocks is the most significant mining activity in the state of Paraná, particularly in the Metropolitan Region of Curitiba (RMC). Data from the National Mining Agency (ANM) indicates that between 2002 and 2022, the exploitation of carbonate rocks contributed to 27.5% of the revenue from the Financial Compensation for Mineral Exploration (CFEM) in the state. The compensation rate was 2%, and 58.4% of this amount was from the mining of carbonate rocks in the municipalities covered in this study (ANM, 2023). At the beginning of the century, 50% of the mineral production in Paraná was from the exploitation of "limestone", (Guimarães, 2005). The Mining Master Plan of the RMC (MINEROPAR, 2004) states that 59.7% of the CFEM revenue in 2001 resulted from the exploitation of mineral substances such as calcitic limestone, dolomitic limestone, and marble. In addition, 31% of the 1489 mining processes and 30% of the active mining areas in the region were directly related to the exploitation of carbonate lithotypes.

The ANM has identified 726 active mining processes in the study area as for 2022, as shown in Figure 1, information which is available through the SIGMINE. Among the 697 processes that have declared their substance of interest, 480 involve solid substances and mineral water extracted from areas with carbonate rock occurrences. Currently, around 65.5% of the study area's 195,600 hectares are undergoing some form of research or exploitation of solid substances or water resources, with 74,500 hectares situated in occurrence areas of carbonate rock as mapped by BESSER (2021). The RMC contains more than 200 caves (CANIE, 2022), with at least 94 of them located within our study area. These caves are located into carbonate rocks from different geological formations of the Açungui Group - Neoproterozoic (FIORI and GASPAR, 1993). The region has significant mineral resources that fulfill a substantial portion of Paraná's economic and social needs, but mining activities have led to various negative environmental impacts, may causing serious damage to the speleological, biological, and paleontological heritage linked to the karst cavities of the RMC. The Paraná Speleological Studies Group (GEEP-AÇUNGUI, 1992; 1995; 1997) and associated researchers have been documenting the environmental impacts on karst caves since the 1980s (SESSEGOLO et al., 1993; 2001a; LINO and ALIEVI, 1980). It has been observed that mining activities in areas with carbonate rock occurrences cause geomorphological modifications. This was pointed out by Pinto (2011) in their study of the Rio Branco do Sul municipality. Water pollution, deforestation, improper use by the public, mass tourism, mining, urban expansion, and civil interest works were the major environmental conflicts in karst areas identified by Sessegolo et al. (2001b). They also mention that caves are being converted into religious temples, garbage and sewage dumps, and water reservoirs. Additionally, the presence of housing in risky areas, including steep terrain, and abandoned mining sites worsen the situation.

According to Guimarães (2005), mining activity in the RMC was consolidated in the 1960s, without proper environmental planning and a "collective consciousness". Rebelo et al. (2003), pointed out that the region's mining sector may not be sustainable due to poor scientific knowledge, no use of technological methods, and the occupation of traditional mining areas. In this context, Nascimento (2012), based on the characteristics of the regional relief, suggested different types of exploitation (mining, mineral water, tourism) in the karst systems in the border region of the Iguaçu and Ribeira river basins, indicating exploratory criteria based on exposure levels of karst systems conditioned by the relief.

It's important to recognize that legal measures to safeguard caves as federal property have only been introduced relatively recently in Brazil. Specifically, the Ordinance No. 887/1990, the National Program for the Protection of Speleological Heritage (2004), and Federal Decree No. 6,640 in 2008 (and its subsequent

amendments) came into force only fifty years after the first mining exploration requests were officially recorded in the study area. Over the past few decades, there have been two key milestones in the preservation of Brazil's speleological heritage: i) the establishment of a minimum protection area of 250 meters around the cavities, and ii) the classification of natural underground cavities based on their ecological, biological, geological, hydrological, paleontological, scenic, historical-cultural, and socioeconomic attributes, with varying degrees of importance determined as maximum, high, medium, or low.

Spaceborne remote sensing data is a relatively recent development when compared to mining activities that have been around for decades or centuries. However, remote sensing has the advantage of providing data that is not dependent on government/political changing vision or biased from regulated mining activities.

Satellite optical sensors like the ones onboard the Landsat series, which provide free access to data and have decades-long temporal series, allow for the determination of mining advances and changes in land use and cover through different mapping methods. Previous studies by Diniz (2014) and Latifovic et al. (2005) have identified significant growth in the mined area of the Iron Quadrangle - MG and the central region of Canada, respectively, through the analysis of Landsat 5 series of images.

This study aims to analyze the expansion of mining activity in the northern region of Curitiba from the 1980s to 2022, using Landsat 5 TM, Landsat 7 ETM+, Landsat 8 OLI sensor images, official data from ANM between 2002 and 2022, and mining process data available in SIGMINE since the 1930s. The satellite imageries were processed with Google Earth Engine (GEE) to map the mining activities in the study area. Although mining is not the only activity that conflicts with the preservation of speleological heritage and regional biodiversity, this study focuses on analyzing the impact of mining in the study area.

II. MATERIALS AND METHODS

The geospatial data obtained from SIGMINE for 2021 were utilized to identify official records and phases of mining processes as recorded and maintained by the National Mining Agency (ANM). We filtered these data spatially, separating mining processes: i) across the whole study area, ii) across areas containing carbonate lithotypes (BESSER, 2021) and, iii) for the 94 natural underground cavities registered in the National Speleological Information Registry (CANIE, 2022) within the study region (Figure 1).
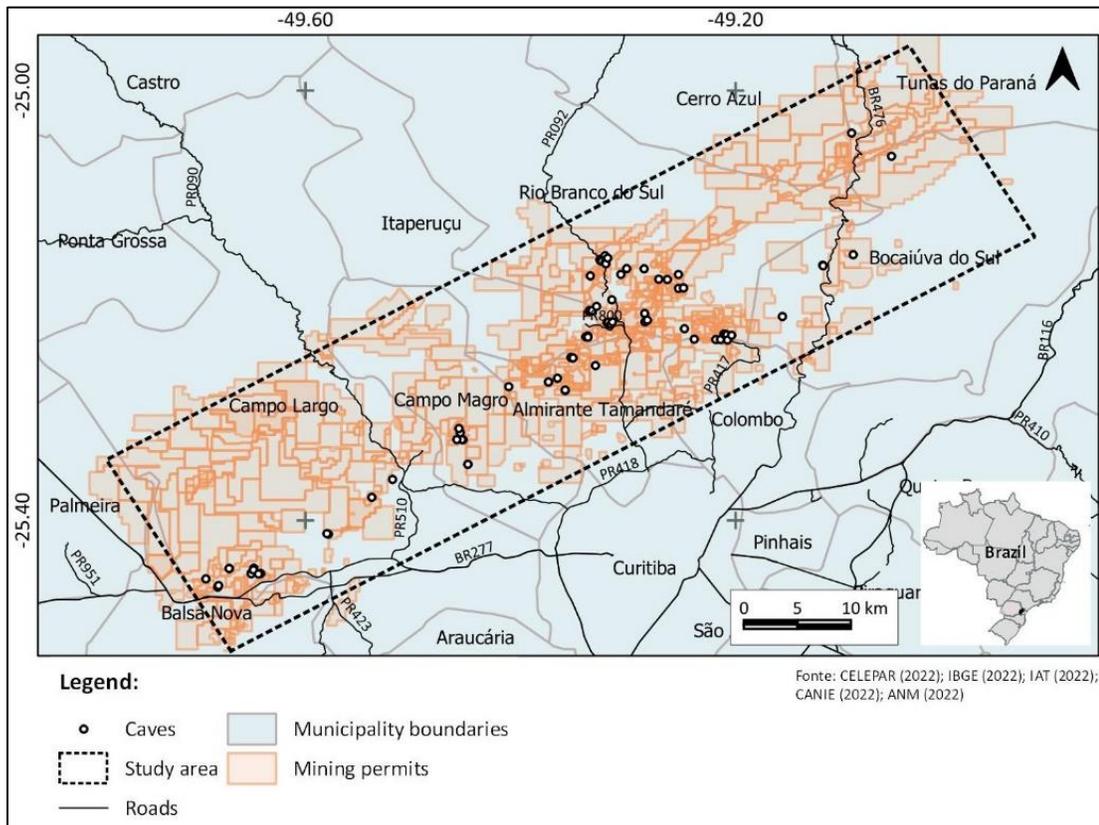
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Figure 1: Location and access points of the study area and distribution of mining requests partially or fully contained within the study area.

The CFEM revenue data between 2002 and 2022 were filtered for the following substances: limestone, calcite, dolomite, marble, and mineral water. Such data set was obtained from the Interactive Brazilian Mineral Yearbook Panel (2023), provided by the ANM, and used to measure the growth of mining activity in the 11 municipalities covered by the study area until 2022.

Land use and land cover changes were mapped using the Google Earth Engine (GEE) platform. Scripts were developed in the JavaScript programming language, which can be accessed at <https://code.earthengine.google.com/ddf61d8c0b812b2e7b711213f833b9c2>. The historical Landsat images were classified to differentiate the spectral responses of the following targets of interest: mining areas (mining activity in carbonate rocks), water bodies (rivers, lakes, and reservoirs), vegetation (occurrence of vegetation cover), and urbanized areas (urban or industrial clusters). Other classes, such as exposed soil, were disregarded. The images from Landsat 5, 7, and 8 satellites were filtered based on the period of interest (Table 1), cloud cover less than or equal to 5%, and pixel quality of the image collection (pixel with maximum value for each spectral band). The latest was done to generate a temporal composition of the best pixels in each period considered, although such practice may favor images with spectral responses influenced by seasonal variations. The term "decade" here does not refer to a period of 10 years but to the period chosen to represent that decade. Due to

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frequent cloud cover, the temporal composition had to use images from 2 to 3 years to generate a cloud-free image within the study area.

The image classification was performed using the Random Forest (RF) machine learning algorithm, using the spectral bands presented in Table 1 as input parameters to train the classifier. RF is a machine learning algorithm that involves learning multiple weak decision trees to generate a stronger decision tree, which is used for regression or classification (BREIMAN, 2001). The classes were defined as follows: 1) "mining areas" (mining in carbonate rocks); 2) "water bodies"; 3) "vegetation"; and 4) "urbanized areas".

As part of the validation process, we quantified the uncertainties of the classification by computing the confusion or error matrix. This matrix provides a comprehensive assessment of overall accuracy, user accuracy, and producer accuracy. For those interested in further details, we have provided data on the number of collected samples at <https://code.earthengine.google.com/ddf61d8c0b812b2e7b711213f833b9c2>.

Table 1. Summary of images analyzed on Google Earth Engine and overall accuracy by period.

Period	Satellite	Sensor	Bands analyzed	Overall Accuracy
1980	01/01/1987 - 31/01/1989	5/TM	4,3,2	96%
1990	01/01/1997 - 30/12/1999	7 ETM+	4,3,2	95%
2000	01/01/2005 - 31/12/2008	7 ETM+	4,3,2	74%
2010	01/01/2016 - 31/12/2018	OLI	5,4,3	98%
2020 - 2022	01/01/2020 - 31/12/2022	OLI	5,4,3	97%

Font: Elaborated by the authors

Spatial analysis, map layout design, and data spatialization were performed using the QGIS 3.16.10-Hannover software (QGIS, 2023). The data was obtained from ANM, CPRM, ITCG, and analyses conducted in GEE.

Analysis of cave registries were used to identify environmental impacts in the study area over the past few decades. The primary source for recording these occurrences and their effects on the speleological heritage of the RMC is the GEEP-Açungui. Nevertheless, it is noteworthy that the GEEP has undergone several management changes, and the transformation of spatial data has caused inaccuracies that are challenging to quantify in cave locations. These inaccuracies may difficult spatial analyses.

To establish protective boundaries around mining sites that contain caves listed in the CANIE (2022), a 250 meters radius buffer was implemented. This distance was determined by Resolution CONAMA No. 347,

which was issued on September 10, 2004. The resolution outlines the scope of influence and requisite actions to preserve biodiversity and safeguard the national speleological heritage.

III. RESULTS AND DISCUSSION

According to the land use and land cover classifications carried out in GEE from the 1980s to 2022, there has been a growth of 363% in the areas classified as "mining areas" (Figures 2 and 3). The data from the 1980s allowed for the classification of 641 hectares as "mining areas", with an 11% increase in the 1990s, reaching 709 hectares. In the 2000s, the growth compared to the previous decade was 68%, reaching 1196 hectares. In the 2010s, there was a less pronounced growth of only 10%, reaching 1326 hectares. Finally, from the 2010s to 2022, a significant increase of 75% compared to the previous decade was observed, reaching 2330 hectares (Figure 2). It is important to note that the growth identified between 1980 and 2022, based on Landsat series images, only represents the expansion of the mined area and not the volume exploited in bench mining. Figure 4 presents the mining areas in the 1980s and the mining areas observed in the 2020s.
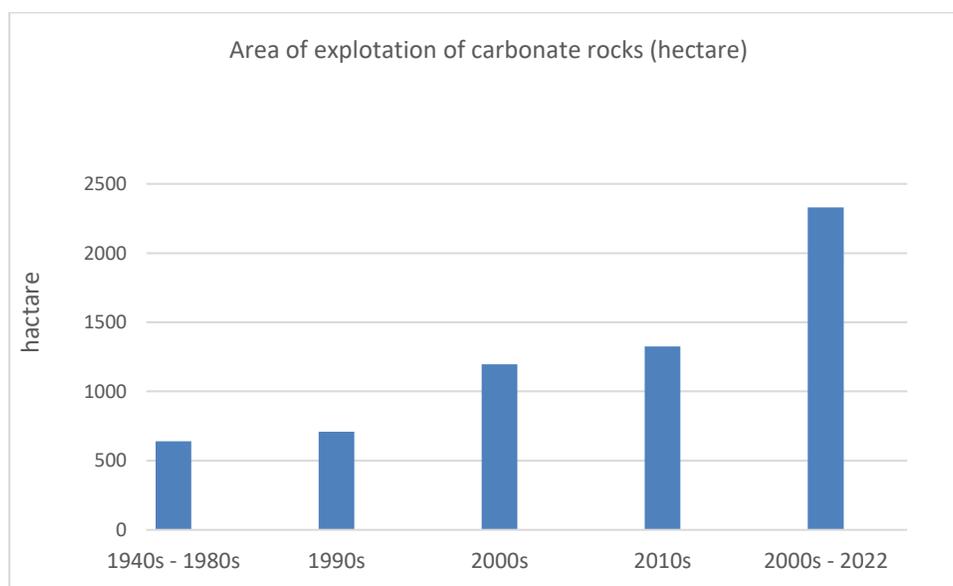

Figure 2: Growth of carbonate mining area in the studied time series. The "x" axis represents the temporal interval considered, and the "y" axis represents the area in hectares.

Based on research conducted by GEEP-Açungui in 1995, it was discovered that out of the 76 caves recorded in the RMC, 39 were destroyed, 15 were partially destroyed, 18 were at risk of destruction, and 3 were being used inappropriately. Unfortunately, only one cave was found to be preserved. These findings indicate that roughly 50% of the recorded caves had been destroyed.
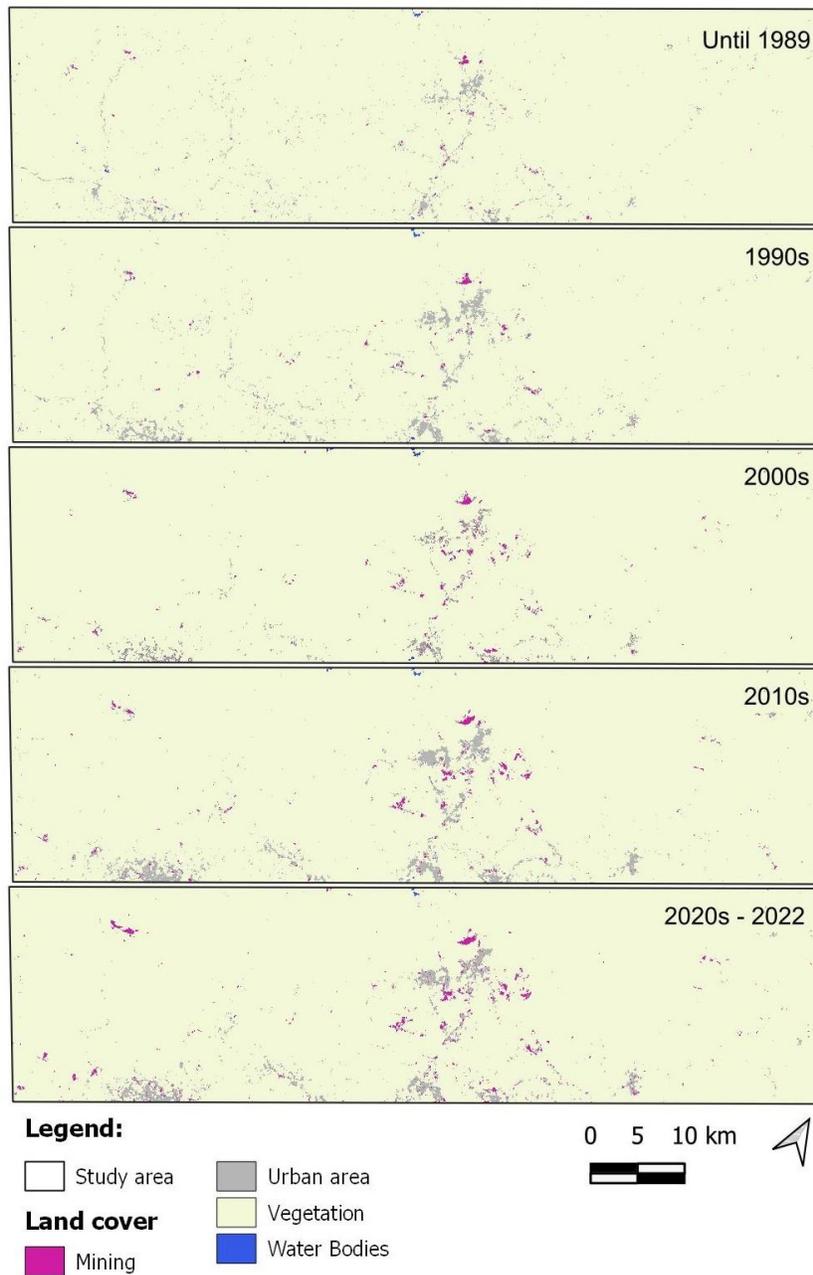
Figure 3: Land use coverage for the analyzed time series, as generated on Google Earth Engine. Additional information in Table 1.

Figure 4: Comparison of land use coverage classified as "mining" in the 1980s and 2020s.

In the early 2000s, Guimarães (2005) identified 198 mining areas in the Capiru Formation, which is the primary occurrence belt of carbonate rocks in the study area. Out of these areas, 107 were active, 43 were inactive, and 24 were abandoned. These findings support the observed slowdown in mining growth during the 2010s in the RMC (Figure 2).

Our research analyzed the effects of mining activities on cave occurrence zones. By cross-referencing the mining areas detected in GEE with the cave registry of CANIE (2022). We discovered that there were 31 to 33 caves within 250 meters of one or more active mining areas from the 1980s to 2022. Interestingly, the number of caves in proximity to mining operations decreased during the 2010s.

Figure 5 illustrates the buffer zones in the occurrence area of four caves in Rio Branco do Sul-PR municipality during the 1980s, 1990s, and 2000s. The figure highlights that during the first two decades, Bento Cave and Rio Branco I and II caves were located within 250 meters of an active mine. However, in the 2000s, mining activities were suspended, and the spectral response of the mining area changed due to vegetation growth. We suggest that compliance with environmental laws and/or economic feasibility resulted in a reduction in the number of caves with mining activity in their influence areas.

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Legend:

○ Caves 2022 - CANIE
▭ Buffer 250 m - 1980s
▭ Buffer 250 m - 1990s
▭ Buffer 250 m - 2000s

Figure 5: Example of buffer zones around caves through time. Note that the mine near Rio Branco I and II caves and Bento Cave have vegetation, indicating the deactivation of mining in the area.

Among the 93 karstic cavities present in the study area, 85 are located in areas that require mining authorization at ANM (CANIE, 2022; ANM, 2023). Currently, there are 22 mining processes with cave presence, with 21 in the mining concession phase and one in the mining request phase (ANM, 2023). This means that most of the caves are situated in areas that are either being mined or are suitable for mining.

Figure 6 shows the evolution of CFEM revenue over the past twenty years, which was derived from the exploration of solid substances (limestone, dolomite, and marble) in the municipalities that are partially covered by the study area. The trend of growth in CFEM collection values, which totaled over R$ 61.3 million in the considered period, reflects the increasing need for mineral resources in recent years, and the consequent increase in mineral exploration in the region. In 2003, there were 475 mining processes throughout the RMC

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with the "Principal Substance" declared as "Limestone calcitic, dolomitic, marble" (MINEROPAR, 2004). However, in the study area alone, which covers 11 (partially) out of 29 municipalities of the RMC, there were 480 mining processes in 2021 (SIGMINE, 2021), showing the growth of mining activity in the last two decades.
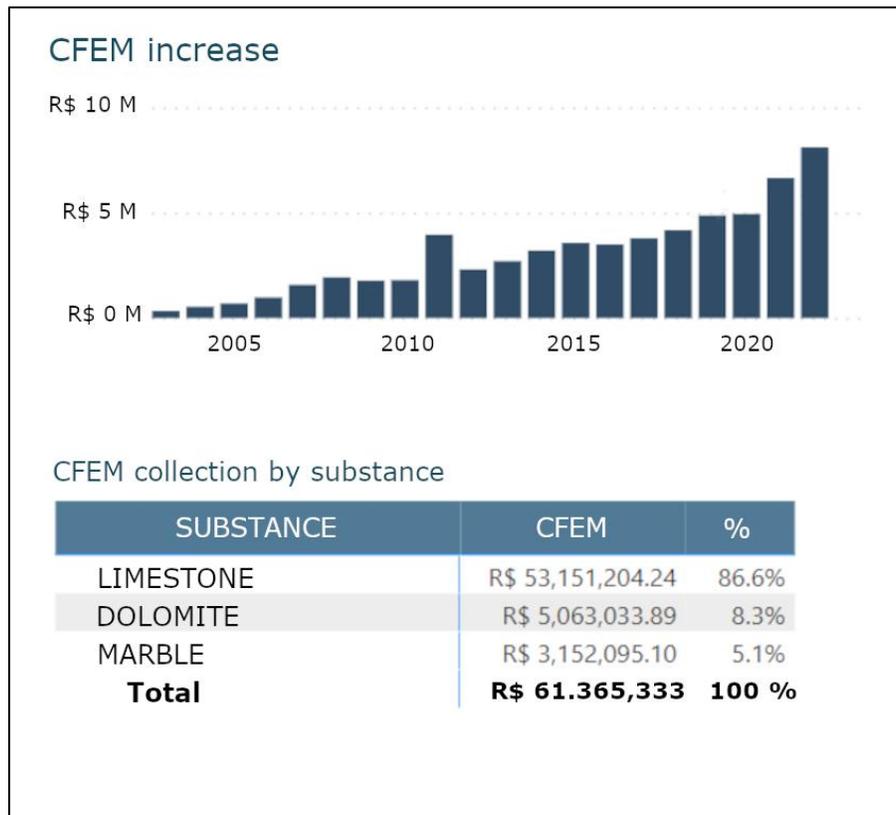

Figure 6: Evolution increase of CFEM increase between 2000 and 2022 for the solid substances "limestone," "dolomite", and "marble" (ANM, 2023).

Sessegolo et al. (1996) estimated that the RMC had lost at least 50% of its speleological heritage by 1995. The calculation considered unregistered caves and those without historical records, as well as mining activities that date back to the late 18th century. In a subsequent study, Sessegolo et al. (2001b) noted that urban expansion in the RMC had intensified environmental impacts, which are likely to worsen as the regional karst aquifer is exploited further. This activity is of strategic importance to the RMC.

It's important to note that the systematic mapping of karstic cavities in the RMC didn't begin until the second half of the 1980s (coinciding with the GEEP-Açungui foundation), summing over fifty years since carbonate mining started in the region, and a decade after Landsat 5 satellite became operational. Although hundreds of cavities have been mapped in recent years, not all existing caves in the region are covered by the current cadaster. A significant portion of the regional speleological heritage was probably destroyed before

being mapped. There are numerous caves yet to be discovered, and many discoveries to be made within the registered caves.

It is crucial to consider the impact of mining expansion on the existence of caves. Some caves were only discovered after mining operations began, and regulations to protect the environment were only put in place after the 1988 Constitution. This research highlights a few discrepancies that exist between mining and preserving speleological heritage. In some instances, mining companies were not aware of such discrepancies, as the caves were only discovered because of the progress of mining activities. Historical documentation from GEEP-Açungui reveals that early mining endeavors in the area utilized cave entrances as the starting point for mining operations. Because of the topography, vegetation coverage, mining techniques, lack of environmental consciousness, and the dearth of legal preservation rules, numerous caves in the RMC were destroyed.

The extraction and processing of lithological material, particularly to produce lime, cement, and construction aggregates, can significantly impact the environment. Windborne particulate matter can spread over nearby vegetation and infrastructure, causing atmospheric pollution. Water and noise pollution are also common, and its intensity varies depending on the processing methods used following mineral extraction.

It's worth noting that in some cases, windborne particulate matter can overestimate the size of active mining areas in land use classification, may affecting the spectral response of targets in the satellite imagery. However, the spread of pollution can also be used to determine the expansion or contraction of mining activity and compliance with legal regulations for mitigating atmospheric pollution, as illustrated in Figure 7.

Figure 7: Vegetation and nearby infrastructure are covered in pollution resulting from lime production using carbonate rocks. Almirante Tamandaré-PR. Source: authors.

This study is subject to certain limitations as cloud-free images were unavailable for certain years analyzed and it was challenging to differentiate targets with similar spectral responses, such as exposed soil, urban areas, and areas near to the processing of lithological material. Furthermore, there is a dearth of official historical records on the environmental impacts of RMC caves. Despite these limitations, the study drew on ANM data and historical reports from GEEP-Açungui, providing a solid foundation for the research, though there is a possibility of CFEM tax evasion.

IV. CONCLUSIONS

The mining of carbonate rocks in the Metropolitan Region of Curitiba (RMC) has increased significantly over the past four decades. This growth can be observed through the increase in areas classified as "mining areas" and the collection of the Financial Compensation for Mineral Exploration (CFEM). However, this economic development has come at a cost, as there have been significant negative environmental impacts on the speleological heritage of the RMC.

The analysis of satellite imagery revealed that areas with spectral response from carbonate mining have grown over 300% between 1980 and 2022, indicating a considerable geographical expansion of the mining activity. Besides this, the historical records from the Speleological Studies Group of Paraná (GEEP-AÇUNGUI) point to partial or total suppression of caves since the mid-1980s.

The main limitations to using remote sensing data in this study were the atmospheric dispersion of particulate matter from the processing of lithological material and the similarity of the spectral response of areas with exposed soils. These limitations could potentially overestimate the area classified as "mining areas". Therefore, data from ANM, CANIE, GEEP-Açungui, and others were fundamental in identifying the growth of mining activity and its impacts on the regional karst.

It is crucial to expand knowledge and improve environmental management by the various government spheres, especially at the state level, which oversees the environmental licensing processes of economic activities. This will ensure that the speleological heritage is effectively studied and registered by current technical and legal regulations.

The proposition of compensatory measures of mining activities in karst areas should be reviewed and expanded in the RMC. The agricultural production of the Paraná, for example, which is consistently among the largest in Brazil, is directly linked to the supply of agricultural lime from carbonate rocks present in the study

area. This fact should motivate the proposal of specific compensatory measures that promote the preservation of the speleological heritage.

Acknowledgements

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