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Potential mining impacts on ecosystem services and biodiversity on Brazil's quartz and iron mountains

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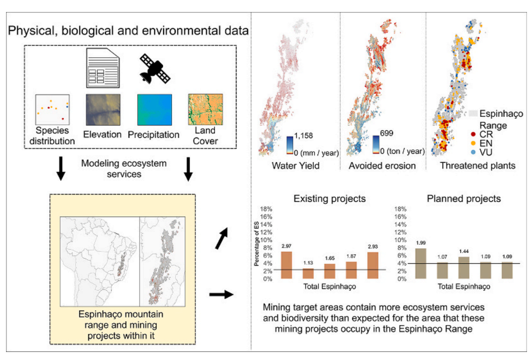
HIGHLIGHTS

- The Espinhaço Range is currently the target of 3668 mining projects.
- Mining projects overlap with hotspots of ecosystem services and biodiversity.
- We identified 639 threatened species in the Espinhaço Range.
- Assessing ecosystem services and biodiversity is key to responsible mining planning.
- Actions are needed to reduce mining impacts in conservation priority areas.

GRAPHICAL ABSTRACT



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ABSTRACT

Land use and land cover changes (LULCC) driven by mining expansion result in negative environmental impacts well beyond the mining pit. We assessed the potential impacts of mining and quarrying expansion on ecosystem services (ESs) and biodiversity in the Espinhaço Range, a center of species diversity and endemism that provides water for nearly 50 million people and has been increasingly affected by these activities. We modeled water yield and sediment retention in InVEST using 2022 LULC, climate, and biophysical data. We also evaluated carbon storage and the geographic distribution of threatened vascular plants and terrestrial vertebrates using publicly available datasets. We categorized active mining processes into existing projects (already active or in advanced stages of implementation) and planned projects (those undergoing approval processes). We calculated a ratio by

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Threatened species
Water security

dividing the percentage of ESs and biodiversity within project areas by the percentage of the area occupied by the mining projects in the Espinhaço Range to evaluate whether mining target areas overlap with hotspots of ESs and biodiversity. The 1360 existing areas targeted for mining provide nearly 3-fold more water and more biodiversity relative to their geographic range, while the 2308 areas targeted for future planned projects provide 2-fold more water and 1.44 times more sediment retention than would be expected for their geographic range. More than 56% of existing projects and 46% of planned projects overlap with critical areas for ESs. Additionally, 30 threatened species had more than 30% of their geographic range overlapping with existing and planned mining and quarrying projects. Our results provide evidence that mining projects pose a potential threat and overlap with key areas for both ESs and biodiversity. Therefore, we indicate measures to mitigate the impact of mining and quarrying on ESs and biodiversity in the Espinhaço Range.

1. Introduction

Mining is among the main anthropogenic drivers transforming landscapes globally with profound, long-lasting effects on ecosystems (e.g., Sonter et al., 2017; Duarte et al., 2022). The growing demand for energy transition minerals raises concerns about the environmental and socio-economic impacts of mining (Giljum et al., 2022; Sonter et al., 2023). These impacts include the suppression of vegetation cover through deforestation, edaphic degradation due to topsoil removal, accelerated urbanization, and the expansion of road infrastructure (Fernandes et al., 2014, 2018; Giljum et al., 2022). In addition, mining often promotes the expansion of monocultures for charcoal production and causes air and water pollution by siltation of water bodies and contamination by heavy metals (Sonter et al., 2014; Macklin et al., 2023). These environmental changes have direct implications for public health, through exposure to toxic elements and impairment of water quality, and contribute to reducing the availability of habitats essential for maintaining endemic species (e.g., Pena et al., 2017; Macklin et al., 2023). In synergy with the impacts imposed by climate change, land use and land cover changes (LULCC) amplify the effects on species distribution, often reducing their range (Corlett and Tomlinson, 2020), consequently, increasing threats to biodiversity while diminishing the provision of several ecosystem services (ESs) (e.g., Fernandes et al., 2020; Hoffmann et al., 2020).

ESs are the benefits that people obtain from ecosystems, either directly (e.g., water, food) or indirectly (e.g., water infiltration, pollination) (Reid et al., 2005; Tavares et al., 2019). Natural ecosystems provide multiple ESs (Díaz et al., 2015, see www.ipbes.net), including water security, as undisturbed vegetation and soils regulate streamflow (Anjinho et al., 2024; Rodrigues et al., 2025) and help control erosion by holding back sediment (Gageler et al., 2014). In contrast, mining causes multiple impacts on ES due not only to open-pit extraction methods (i.e., removal of near-surface minerals through horizontal benches and the disposal of tailings elsewhere; Altiti et al., 2021) but also to the infrastructure required for mineral extraction and processing (Neves et al., 2016; Sonter et al., 2023). Deeply modified landscapes increase erosion, which silts up springs and streams and can trigger regional social conflicts over water use, such as ore transportation, ultimately reducing the water provision. Mining also contributes to climate regulation loss (Siqueira-Gay et al., 2020). For example, deforestation caused by mining in the Amazon reduces greenhouse gas mitigation, leading to an annual economic loss of US$ 2.2 billion (Siqueira-Gay et al., 2020). Additionally, mining drives biodiversity loss at both local and regional scales, primarily through the destruction of critical habitats for native species, particularly endemics (Sonter et al., 2014). These studies underscore the need to assess the impacts of mining on ESs and to identify regions that are critical for the conservation of both ESs and biodiversity (Moomen et al., 2020).

The interdependence between ecosystems and biodiversity highlights the importance of securing ESs in the planning and implementation of effective public policies and in fostering socio-environmental resilience. This understanding is crucial for advancing sustainable development strategies (Díaz et al., 2015). In the context of mining activities, Brazil represents a region of high ecological vulnerability. This country is a global leader in both the extraction and reserves of key mineral resources (IBRAM, 2023). This position underscores the strategic economic importance of the mining sector in Brazil but also highlights its potential to intensify environmental pressures on already vulnerable ecosystems. Addressing these challenges requires integrative evidence-based scientific approaches to assess and mitigate impacts, while guiding the mining sector toward alignment with sustainable development frameworks to safeguard both ecological integrity and long-term industry viability.

In this context, the Espinhaço Mountain Range represents a unique scenario where biodiversity, strategic ESs, and mining interact, generating many socio-environmental conflicts (Fernandes et al., 2020). The Espinhaço Range, the longest mountain range in Brazil and the second-largest in South America, extends over 1200 km across eastern Brazil, spanning three biomes: the Caatinga, the Cerrado, and the Atlantic Forest (Fernandes, 2016). The Espinhaço Range is historically marked by open-pit gold and diamond mining, with extensive LULCC beginning in the 17th century with the establishment of towns and roads (Neves et al., 2016). Despite the significant impacts of open-pit mining and quarrying, the Espinhaço Range supplies a wide range of raw materials (e.g., iron, gold, aluminum, nickel) that are critical for the energy transition. It also provides several ecosystem services, including resources needed for the maintenance of traditional populations, tourism, pollination, climate regulation, carbon sequestration, and water for millions of people in eastern Brazil (e.g., Neves et al., 2016). The Espinhaço Range is also a key biodiversity repository due to several areas of endemism (e.g., Echternacht et al., 2011; Resende et al., 2013; Barbosa et al., 2015). The mountaintops are dominated by rupestrian grasslands (*campo rupestre* in Portuguese), a megadiverse ecosystem characterized by exceptionally high levels of plant and animal diversity (Silveira et al., 2016; Oswald et al., 2025). Yet these grasslands are increasingly threatened by real estate development, mining, agribusiness, and other anthropogenic pressures (Fernandes, 2016; Fernandes et al., 2020).

Although some studies have examined sustainable management, ESs, and the socio-environmental impacts of mining in the Espinhaço Range (e.g., Pena et al., 2017; Neves et al., 2016; Monteiro et al., 2018), a comprehensive assessment of the potential environmental impacts of mining across the entire region is still lacking. Moreover, socio-environmental impacts are typically assessed in isolation for each mining project through environmental impact studies or reports required by law in Brazil (see Bragagnolo et al., 2017). This approach makes it difficult to fully understand the cumulative impacts of ongoing and future mining projects. In this context, the development of ESs modeling tools, combined with the availability of large datasets, has made it possible to assess the impacts of large-scale economic activities, an otherwise difficult task if relying solely on field sampling due to the extensive effort required (Meraj et al., 2022). Consequently, spatial analyses using these modeling tools are essential for assessing the impacts of human activities, identifying pathways for more sustainable development, and aligning economic activities with the conservation of ESs and biodiversity (Meraj et al., 2022). Moreover, they facilitate integrated assessments of environmental impacts and improve the capacity to predict the future consequences of new projects (Duarte et al., 2016).

Our objective was to evaluate the potential impacts of mining and quarrying expansion on the provision of three key ESs (e.g., water yield, carbon storage, and sediment retention), and on the threatened vascular plants and terrestrial vertebrates in the Espinhaço Range. Given the environmental, political, and socio-economic heterogeneity across the Espinhaço Range, we also assessed the potential impacts of mining separately for the portions of the Espinhaço Range within each of the three biomes: Caatinga, Cerrado, and Atlantic Forest. We modeled water yield and sediment retention in InVEST using LULC data (Mapbiomas, 2023) and climate data (e.g., Fick and Hijmans, 2017). We evaluated carbon storage using rasters (i.e., data stored in a matrix of georeferenced pixels) provided by Englund et al. (2017) and Vasques et al. (2021). We used data on threatened species from SALVE (ICMBio, 2019) and CNCFlora (2023) (Ribeiro et al., 2018) to assess biodiversity. We categorized active mining processes into existing and planned projects following Ferreira et al. (2014) and Villén-Pérez et al. (2018). We calculated a ratio by dividing the percentage of ESs and biodiversity within project areas by the percentage of the area occupied by the mining projects in the Espinhaço Range to assess potential impacts of mining expansion on ESs and biodiversity. Our results provide critical evidence to guide responsible mining planning in the Espinhaço Range.

2. Methods

2.1. Study area

The Espinhaço Range spans from 21°01′49.3" S and 44°29′37.9" W to 9°40′43.4" S and 41°00′39.2" W, extending 1369 km through Minas Gerais and Bahia Brazilian states and covering 14 million ha (140,000 km^2) (Fig. S1). The elevation ranges from 237 to 2078 m above sea level (Farr et al., 2007). The climate regime comprises As (tropical with dry summer), Aw (tropical with dry winter), BSh (dry semi-arid low latitude and elevation), Cfb (humid subtropical oceanic climate, without dry season with temperate summer), Cwa (humid subtropical with dry winter and hot summer), and Cwb (humid subtropical with dry winter and temperate summer), with rainy summers and dry winters. The temperature and rainfall vary latitudinally (Alvares et al., 2013), from ~8 mm in the driest month (August) to 200 mm in the wettest month (December), and from 18 °C in the coldest month (July) to 22.4 °C in the warmest month (February) (monthly averages between the years of 1970 and 2000) (Fick and Hijmans, 2017). The Espinhaço Range spans three Brazilian biomes, two of which are biodiversity hotspots: the Cerrado to the east, the Atlantic Forest to the west, and the Caatinga to the north. The climatic, edaphic, altitudinal, and latitudinal variations of the Espinhaço Range result in a diverse array of habitats and microclimates, making it one of most biodiverse regions in the world (Fernandes, 2016).

There is no detailed map for the Espinhaço Range. Then, to delimit the study area, we primarily used the *campo rupestre* vegetation map provided by Fernandes et al. (2014) and Barbosa and Fernandes (2016) (Fig. S1). This vegetation type is typical of high-elevation regions located on the mountaintops of the Espinhaço Range, predominating over 900 m above sea level (Echternacht et al., 2011; reviews in Fernandes, 2016). As the map of *campo rupestre* covers regions beyond the extent of the Espinhaço Range, we cut out the map using the minimum and maximum latitude and longitude limits of the Espinhaço Range Biosphere Reserve (RBSE) (Mucida et al., 2019). The RBSE covers 10.2 million ha and includes 172 municipalities in the state of Minas Gerais (IDE-Sisema, 2021). As the Espinhaço Range also extends into Bahia state, which is not included in the boundaries of the RBSE, we retained the *campo rupestre* vegetation in the portion of Bahia. Small patches of *campo rupestre* vegetation found in the east of the state of Bahia were not considered, as they were isolated from the rest of the Espinhaço Range (Fig. S1).

Given that the Espinhaço Range comprises not only *campo rupestre* vegetation on mountaintops but also diverse types of lowland vegetation, we selected all seven-level watersheds (i.e., small watershed units; sensu ANA, 2012) that overlap with the *campo rupestre* vegetation map. This selection was based on two main reasons. First, watersheds are natural units commonly used in public management for water security policies (see Leach, 2006). Second, this approach ensures a consistent and accurate representation of the hydrological flow of rivers (ANA, 2012), which is a key variable for modeling ES (Sharp et al., 2023). Thus, the study area, here referred to as the "Espinhaço Range", includes all level-seven watersheds that overlap the *campo rupestre* map (Fig. S1). This methodology allows for the consideration of both the biological aspects of the Espinhaço Range, such as vegetation, and the human populations living in small towns around the mountain range, who are potentially affected by mining and quarrying expansion.

2.2. Land use and land cover

We used MapBiomas Collection 8, the collection referring to LULC map for the year 2022, maintaining the original 30 × 30 m resolution (MapBiomas, 2023). MapBiomas is a collaborative, multi-institutional global network that provides detailed spatial data on LULC in Brazil and other countries. Along the Espinhaço Range, MapBiomas identifies 19 LULC classes, which we have grouped into 13 classes. Native vegetation covers 61.7% of the Espinhaço Range and includes six classes: forest, savanna, grassland, rocky outcrops, wetland, and dunes/sand spots. Among the natural ecosystem classes, savannas and forests predominate, accounting for 41.8% and 11.0%, respectively (Fig. S2, Tables S1–S2). Anthropogenic land uses cover 38.2% of the Espinhaço Range and include six classes: pastures, mosaics of pasture/agriculture, perennial crops (e.g., coffee, citrus, sugarcane, and other perennials), temporary crops (including soybeans), urban areas, and non-vegetated areas (mining sites and other unvegetated surfaces). Among the anthropogenic land use classes, pastures and mosaics are the largest, occupying 20.2% and 11.8% of the region, respectively (Fig. S2, Table S1). This classification was essential for assigning biophysical values in ES modeling (see water yield section). For visualization, we summarized the 13 classes into native vegetation and anthropogenic land use in Fig. 1A. Full details of each class are provided in the supplementary material and in Tables S1, S2 and Fig. S2.

2.3. Mining projects

We used data on active mining processes in Brazil from the Geographic Information System for Mining (SIGMINE) provided by the National Mining Agency (2021, accessed in November 2023) to analyze the mining projects in the Espinhaço Range. We categorized the projects in two groups based on their licensing phases, following Ferreira et al. (2014) and Villén-Pérez et al. (2018): (i) existing projects, referring to mining and quarrying processes registered, granted, or approved for extraction, including those in the mining concession, licensing, extraction registration, and artisanal mining phases, and (ii) planned projects, which include requests in the mining and quarrying application, licensing application, extraction registration application, and artisanal mining requirement phases. Both groups have some projects containing areas that have already been mined verified via satellite and MapBiomas (2023) at 30 × 30 m resolution raster, which may have started their activities after registering with SIGMINE (2021) or continued previous projects in the same location. Therefore, we removed areas classified as mining by MapBiomas (i.e., areas referred to as industrial or artisanal mineral extraction, with evident soil exposure due to anthropogenic activity) from both existing and planned mining projects. This approach allowed us to estimate the potential impacts of mining expansion while excluding the effects of current mining operations. Fig. 1 displays existing and planned projects along the Espinhaço Range, zooming in on the Iron Quadrangle region, where there is a high concentration of projects in the southern part of the Espinhaço Range. Projects in the

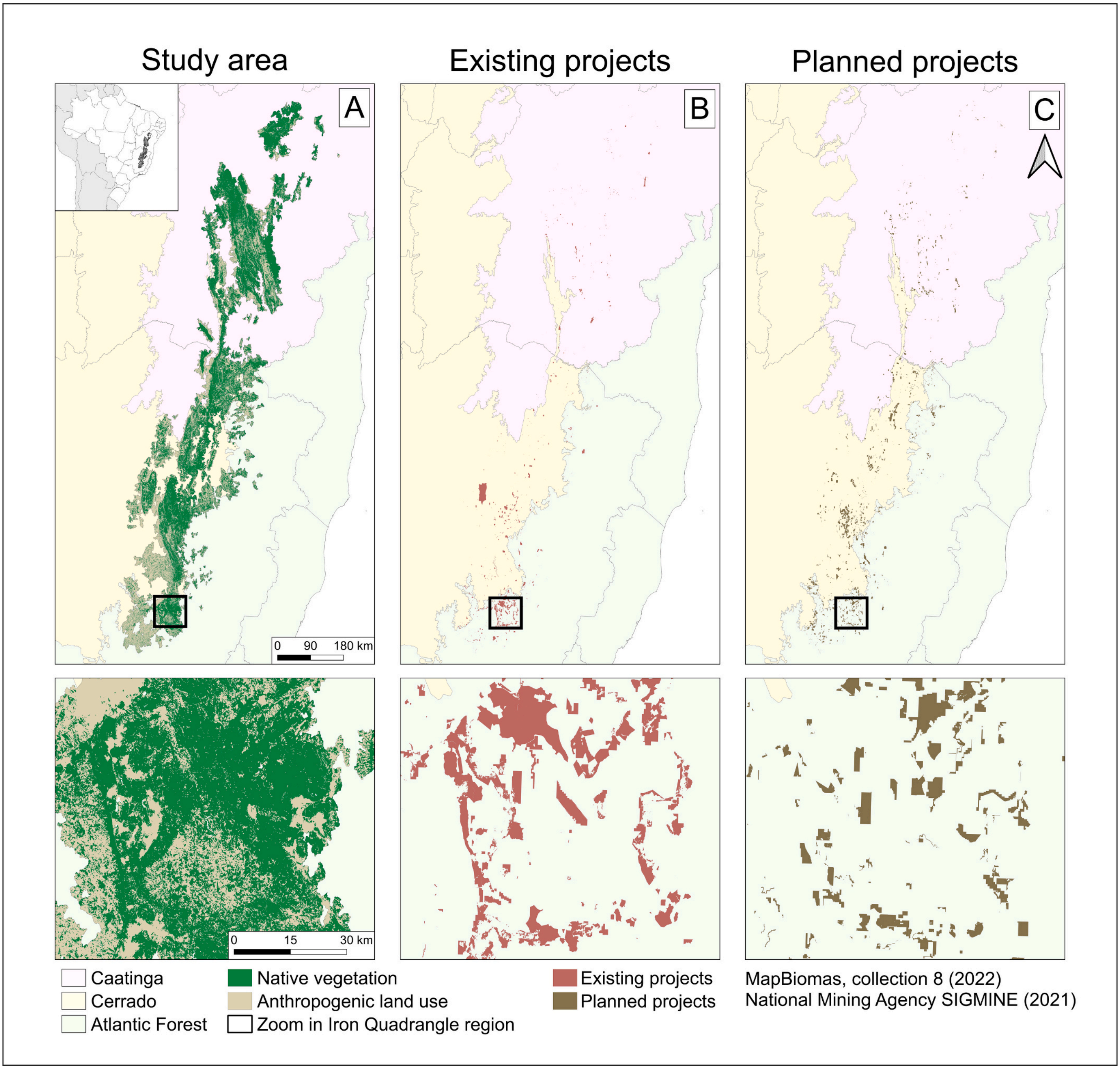

Fig. 1. Location of the study area and its native vegetation and anthropogenic land use and cover across the Espinhaço Range (A), extending from Minas Gerais to Bahia states in southeast Brazil; spatial distribution of existing mining projects (B) and planned mining projects (C); zoom in the Iron Quadrangle region.

research authorization phase, classified as planned projects (Villén-Pérez et al., 2018), were excluded because this phase is preliminary and uncertain and covers a vast area (~43% of the Espinhaço Range) (Fig. S6A). Finally, it is important to note that although mining and quarrying infrastructure impacts extend beyond the mining pits (Sonter et al., 2023), data on infrastructure are not readily available, indicating that our results are severely underestimated.

2.4. Modeling water yield and sediment retention

We used the Seasonal Water Yield and Sediment Delivery Ratio models from InVEST 3.14.0 (Integrated Valuation of Environmental Services and Tradeoffs, Sharp et al., 2023), a widely used GIS tool, to model and map ESs (see naturalcapitalproject.org). The Seasonal Water Yield model provides spatial indices for the contribution of the landscape to water regulation. The main input data required to model this ES include: LULC (obtained from MapBiomas, 2023, original resolution of 30 × 30 m), digital elevation model (Farr et al., 2007; resolution of 30 × 30 m), monthly precipitation in mm (Fick and Hijmans, 2017; resolution of 1 × 1 km), monthly evapotranspiration in mm (Trabucco and Zomer, 2018; resolution of 1 × 1 km), and watersheds boundaries (ANA, 2012). We used the base flow output raster (index of water that reaches water bodies slowly) for the Espinhaço Range (Sharp et al., 2023) at 30 × 30 m resolution to perform the subsequent analyses.

The sediment delivery ratio model provides estimates of production, retention, and delivery of sediment in the landscape. This model also uses LULC, the digital elevation model, and the watersheds boundaries as input data, but it also requires raster data on the susceptibility of the soil to erosion (Godoi et al., 2021; resolution of 250 × 250 m) and raster data on the capacity of rainfall to cause soil erosion (Mello et al., 2013;

resolution of 30 × 30 m). We used the avoided erosion (i.e., the contribution of vegetation to reducing the erosion from a pixel) output raster in our subsequent analyses.

InVEST accepts raster data with different cell sizes as input data. On the other hand, it converts them to match the cell size of the digital elevation model (here 30 × 30 m). We have converted the inputs to 30 × 30 m using the bilinear interpolation method implemented in the terra package in R (Hijmans et al., 2024) in advance to standardize the data and match it with elevation and LULC data, which are the most accurate. Bilinear interpolation is recommended for continuous variables, such as the climate rasters utilized in this study, as it estimates each new pixel value from a distance-weighted average of the four nearest pixels in the original grid. As a result, this approach generates spatial gradients, reducing abrupt transitions between pixels. Despite a discrepancy between the input resolutions, these data are commonly used for modeling in InVEST (e.g., Manhães et al., 2016; Resende et al., 2019, 2021; Kim and Jung, 2020). The methodological details are in the *water yield modeling* and in *sediment retention modeling* sections in supplementary material and in Table S3.

2.5. Estimating carbon storage

We obtained and mapped carbon storage by summing above-ground carbon and organic carbon in the soil. We used the above-ground carbon raster from Englund et al. (2017), at an original resolution of 50 × 50 m, which was converted to 30 × 30 m. Englund et al. (2017) used LULC data, along with an average of available biomass maps, to estimate the Brazilian above-ground carbon map. We also used the soil organic carbon storage rasters provided by Embrapa Solos (Brazilian Agricultural Research Corporation, see https://geoinfo.dados.embrapa.br) (Vasques et al., 2021), at an original resolution 90 × 90 m. Subsequently, we summed the soil carbon across different depth classes (from 0 to 200 cm deep in the soil) and rescaled it to 30 × 30 m resolution. The soil organic carbon maps were estimated by Embrapa Solos using data from soil suborders and Brazilian biomes, climate, and elevation data, and other software (Vasques et al., 2021). The rescaling of both rasters was also done using the bilinear interpolation method (as described in section 2.4). It was necessary to rescale both datasets to a resolution of 30 × 30 m to ensure spatial alignment with the other ESs layers and allow the carbon rasters to be accurately summed.

2.6. Biodiversity

We used georeferenced occurrence records for 563 threatened vascular plant species (e.g., lycophytes, monilophytes, gymnosperms, and angiosperms) and 76 threatened terrestrial vertebrates (e.g., reptiles, birds, amphibians, and mammals) that occur in the Espinhaço Range to represent the biodiversity component. These taxa were selected because they are among the groups with the most consistently available distributional data in the region, enabling robust analyses. Furthermore, many species in these taxa are considered umbrella species, as conservation actions targeting them should extend benefits to other less studied taxa (Roberge and Angelstam, 2004).

We obtained the list of threatened plant species and their occurrence records from the National Center for Flora Conservation, a national reference in providing information on Brazil's threatened flora (CNCFlora, 2023), relating to the 2014 decision on threatened species, which was the most recent one containing occurrence records for Brazil (Ribeiro et al., 2018). We considered the National List of Threatened Species of the Ministry of the Environment and Climate Change (MMA, 2022), along with the regional threatened species lists of the states of Bahia (Bahia, 2017) and Minas Gerais (Minas Gerais, 2010) to compile the list of threatened vertebrate species. We then obtained occurrence records for threatened vertebrate species in our final list from the SALVE/ICMBio repository (ICMBio, 2019). This repository provides refined and updated data on Brazilian fauna and supports extinction risk assessments (ICMBio, 2019). We built a 2 km radius buffer around the occurrence records for each species, following the IUCN criterion for defining the area of occupancy of the species (see Standards and Petitions Working Group, 2006) to represent the distribution area of threatened plants and vertebrates.

2.7. Analyses

We first summed the total amounts for each ES (e.g., water yield, sediment retention, and carbon storage), and calculated the percentage of ESs present within mining project areas related to the total at the Espinhaço Range (Fig. 2A1—A2). Next, we calculated the percentage of area occupied by existing and planned mining projects at the Espinhaço Range to estimate the potential impacts of mining and quarrying expansion (Fig. 2A3—A4). Finally, for each mining group (existing and planned projects), we divided the percentage of each ES within mining projects by the percentage of area occupied by the mining projects in the Espinhaço Range (Fig. 2A2—A4). We repeated the same analyses for each biome (i.e., Caatinga, Cerrado, and Atlantic Forest), dividing the percentage of ESs within the mining projects of each biome by the percentage of the area occupied by the mining projects in that biome (Fig. 2B2—B4). Additionally, we evaluated each mining project individually by dividing the percentage of ESs within a mining project by the percentage of the area occupied by this project in the Espinhaço Range (Fig. 2C2—C4).

As a result, ratios lower than one indicate that mining targets provide less ESs than expected given the area they occupy. In turn, ratios higher than one indicate that mining targets provide more ESs than expected given the area they occupy (Fig. 2D). These ratios allowed us to assess whether mining target areas hold disproportionately high amounts of ESs considering their area, thereby identifying the overlap of mining and quarrying operations with hotspots of ESs (see Eigenbrod et al., 2009; Resende et al., 2021). For biodiversity, we applied the same analytical approach as for ESs. We calculated the percentage of range loss for each threatened species by overlapping their geographic distribution range with mining target areas. We then calculated the average percentage of range loss across all threatened species occurring in targeted areas relative to the total number of species in the Espinhaço Range. Finally, we divided this average by the percentage of the area occupied by the mining projects in the Espinhaço Range. We also repeated the same analyses for each biome and each mining project. The analyses were done using R version 4.3.2 (R Core Team, 2023), mainly with the *sf* (Pebesma and Bivand, 2023) and *terra* (Hijmans et al., 2024) packages. The maps were built in the QGIS program version 3.34.3-Prizren (QGIS Development Team, 2024).

3. Results

Both existing and planned mining and quarrying projects overlapped with substantial areas of native vegetation at risk of being lost due to the expansion of operations (Table S2). The 1360 existing mining requests cover an area of 330,534 ha (2.34%) of the Espinhaço Range, and 5.4% of the *campo rupestre* vegetation. These projects are primarily concentrated in the Cerrado and Atlantic Forest regions, particularly in the southern portion of the Espinhaço Range, at the Iron Quadrangle (Fig. 1B—C). In contrast, the planned projects category included 2308 mining processes, spanning 553,022 ha (3.92%) of the Espinhaço Range, and 3.87% of the *campo rupestre* vegetation with a more widespread distribution along the mountain range (Fig. 1C). Together, existing and planned projects occupy 6.26% of the Espinhaço Range and 9.27% of the *campo rupestre* vegetation.

Among the existing projects, the predominant minerals extracted were iron ore (277 projects) and sand (i.e., granular material with dimensions between 4.8 mm and 0.075 mm, composed mainly of quartzite, La Serna and Rezende, 2009) (237 projects), most located in the southern Espinhaço Range (Table S6). However, the largest mining

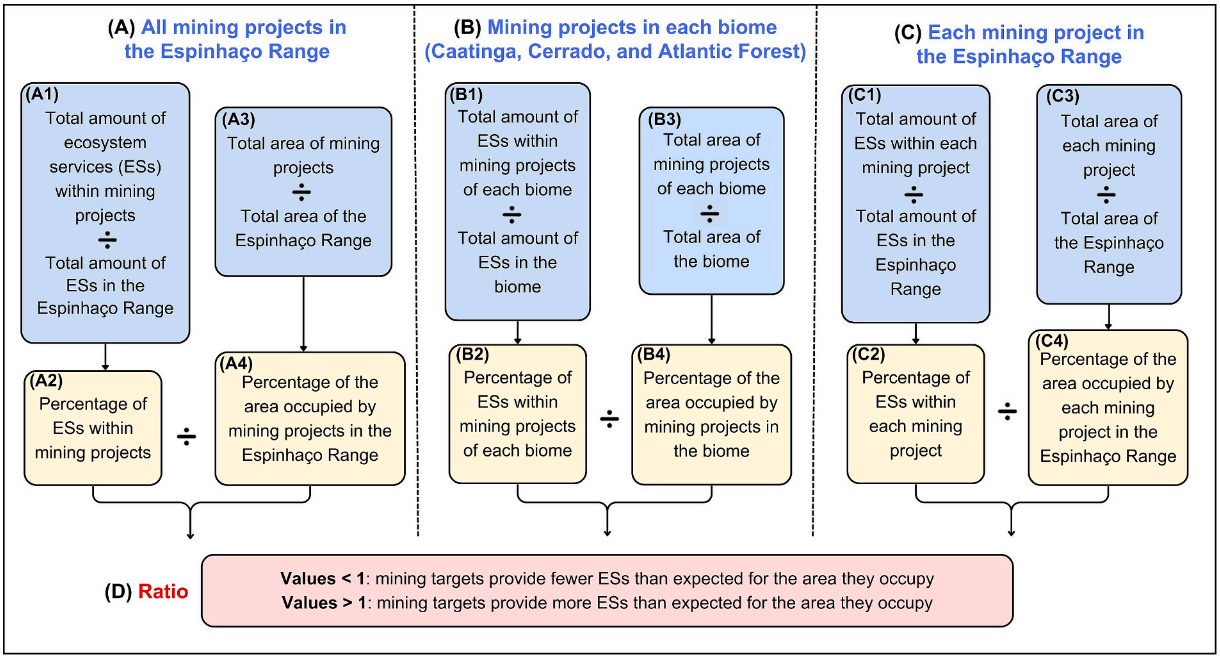

Fig. 2. Workflow summarizing the analytical steps used to estimate the ratio of ecosystem services within mining projects in phases one (blue), phase two (yellow), and phase three (red). Panel (A) shows the calculations for all mining projects in the Espinhaço Range (steps A1—A4). Panel (B) details the same procedure applied to mining projects within each biome (i.e., Caatinga, Cerrado, and Atlantic Forest) (steps B1—B4). Panel (C) presents the analysis performed for each mining project individually (steps C1—C4). In all cases, the final ratio compares the proportion of ESs within mining projects to the expected proportion based on the area they occupy: values less than one indicate fewer ESs than expected, whereas values greater than one indicate more ESs than expected. For biodiversity analyses, we applied the same workflow using the geographic distribution ranges of threatened plant and vertebrate species in shapefile format.

areas are occupied by quartz/quartzite (0.77% of the study area), gold (0.34%), and iron ore (0.43%) (Table S6).

For the planned projects, the most common material extracted were quartz (i.e., crystalline mineral composed of silicon dioxide) (405 projects) and quartzite (i.e., metamorphic rock composed primarily of quartz and other minerals) (395 projects), which were evenly distributed along the Espinhaço Range, covering 1.62% of the total area, as well as sand (294 projects), which was primarily concentrated in the Atlantic Forest biome region. In terms of area, iron ore (0.61%) and granite (0.49%) occupied significant portions of land, following quartz and quartzite (Table S6).

The spatial distribution of the ESs evaluated (e.g., water yield, sediment retention, and carbon storage) showed distinct spatial patterns (Fig. 3A—C). Although the Atlantic Forest covers 17.3% of the territory, it contributed disproportionately to these services with 53.4% of the total water yield, 26.9% of the sediment retained, and 20.4% of the total carbon stocks. In contrast, the Cerrado, which covers 42.8% of the Espinhaço Range, contributed 43.5% of the water yield, 43.6% of the retained sediment, and 44.8% of the carbon storage. The Caatinga, occupying 39.9% of the Espinhaço Range, provided only 3% of the total water yield, while retaining 29.5% of the sediment and storing 34.7% of the carbon.

Regarding biodiversity, the Espinhaço Range is home to 563 threatened plant species, representing 26.5% of the 2119 threatened species in Brazil (MMA, 2022; CNCFlora, 2023). These species were categorized as 104 critically endangered, 326 endangered, and 133 vulnerable (Fig. 3D—E). Threatened plants were distributed across 76 families, but were concentrated in Asteraceae (120 species), Melastomataceae (32), Cactaceae (30), Fabaceae (30), and Orchidaceae (27) (Table S8). Additionally, 76 threatened terrestrial vertebrates have been identified in the study area, including five critically endangered, 31 endangered, and 40 vulnerable species. The most represented Orders are Passeriformes (17 species), Carnivora (8), Squamata (8), Chiroptera (7), and Rodentia (6) (Table S9).

3.1. ESs and biodiversity throughout all mining projects

Considering the entire Espinhaço Range, it is estimated that from 2% to 6% of the ESs evaluated (i.e., water yield, sediment retention, and carbon storage) are provided by areas within existing mining projects, while between 4% and 8% of these services are provided by areas within planned mining and quarrying projects (Fig. 4). Although these percentages may seem relatively small, they are significant when compared to the proportion of the Espinhaço Range occupied by mining projects (2.34% and 3.92% for existing and planned projects, respectively). These disproportionate values indicate that mining projects are located in hotspots for the provision of these ESs. Among the ESs evaluated, water yield stands out, as areas targeted by existing mining projects yield 2.97 times more water than would be expected based on their area. In addition, the planned projects produce 1.99 times more water than expected based on their area. Sediment retention was approximately 1.65 times higher than expected in existing projects, while carbon storage was slightly above the expected values for both existing and planned mining projects.

Regarding biodiversity, the geographic distribution range of threatened species was disproportionately concentrated within mining areas. On average, the proportion of threatened plant distributions overlapping with existing mining projects was 2.93 times higher than expected based on their area, while the overlap for threatened vertebrates was 1.87 times higher than expected (Fig. 4). In planned mining projects, the proportion of the distribution range of threatened plants and vertebrates was 1.09 for both groups, following the proportion expected based on the area covered by the projects (Fig. 4). Species with limited occurrence records (due to insufficient sampling or endemism) were more likely to be significantly affected. Mining projects overlapping the areas of these poorly sampled species therefore pose the biggest potential impact, as shown by the empty areas in Fig. 3D—E. These most vulnerable species are concentrated in the southern Espinhaço Range, in the Atlantic Forest and Cerrado, where mining projects were

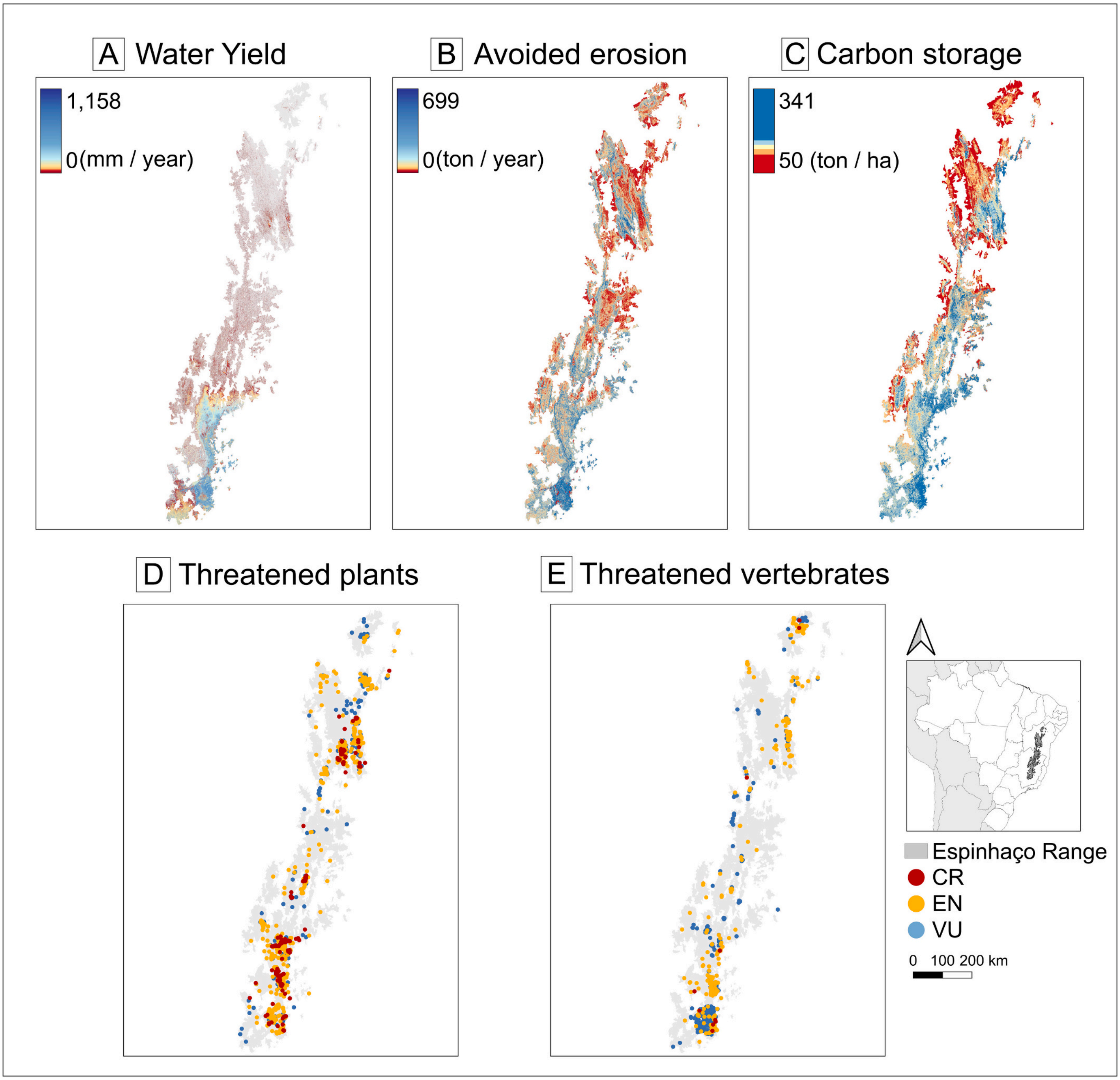

Fig. 3. Spatial distribution of ecosystem services and biodiversity along the Espinhaço Range. (A) water yield, with pixels that do not contribute to the water flow (value = 0) in gray; (B) avoided erosion; (C) carbon storage (above–ground and organic carbon in the soil); (D) occurrence records of threatened plants classified according to the degree of threat of each species; (E) occurrence records of threatened vertebrates. CR: critically endangered; EN: endangered; VU: vulnerable.

concentrated (Figs. 1, 3D—E, S5 in the Supplementary Material).

The potential impact of mining projects was contingent on the surrounding biome. In the Caatinga, both existing and planned mining projects showed impact values on ESs and biodiversity that were either higher than or close to those expected based on the area they occupy. Threatened plants and vertebrates in existing projects were particularly at risk (Fig. 4). However, for planned projects, the impact on species distributions was generally smaller than expected based on the area occupied. In the Cerrado, the impacts on ESs and biodiversity were also higher than or close to expected, with water yield standing out in both categories. The exception in the Cerrado was the distribution of threatened vertebrates in existing projects, which is lower than expected for the area occupied. The existing mining projects in the Atlantic Forest yielded results similar to those observed for the entire Espinhaço Range, suggesting that these projects are in areas important for both ESs provision and biodiversity conservation. However, threatened plants and vertebrates in the planned mining projects in the Atlantic Forest were found to be lower than expected relative to the area occupied by these projects.

3.2. ESs and biodiversity in each mining project

Among the 1360 existing mining projects, 41% showed ratios >3 for water yield than expected for the area they occupy (Fig. 5A), 28% showed ratios >2 for sediment retention than expected by their area (Fig. 5B), and 71% ratios >1 for carbon storage than expected (Fig. 5C). For the 2308 planned mining projects, 35% showed ratios >2 for water yield, while 18% of projects showed ratios >2 for sediment retention

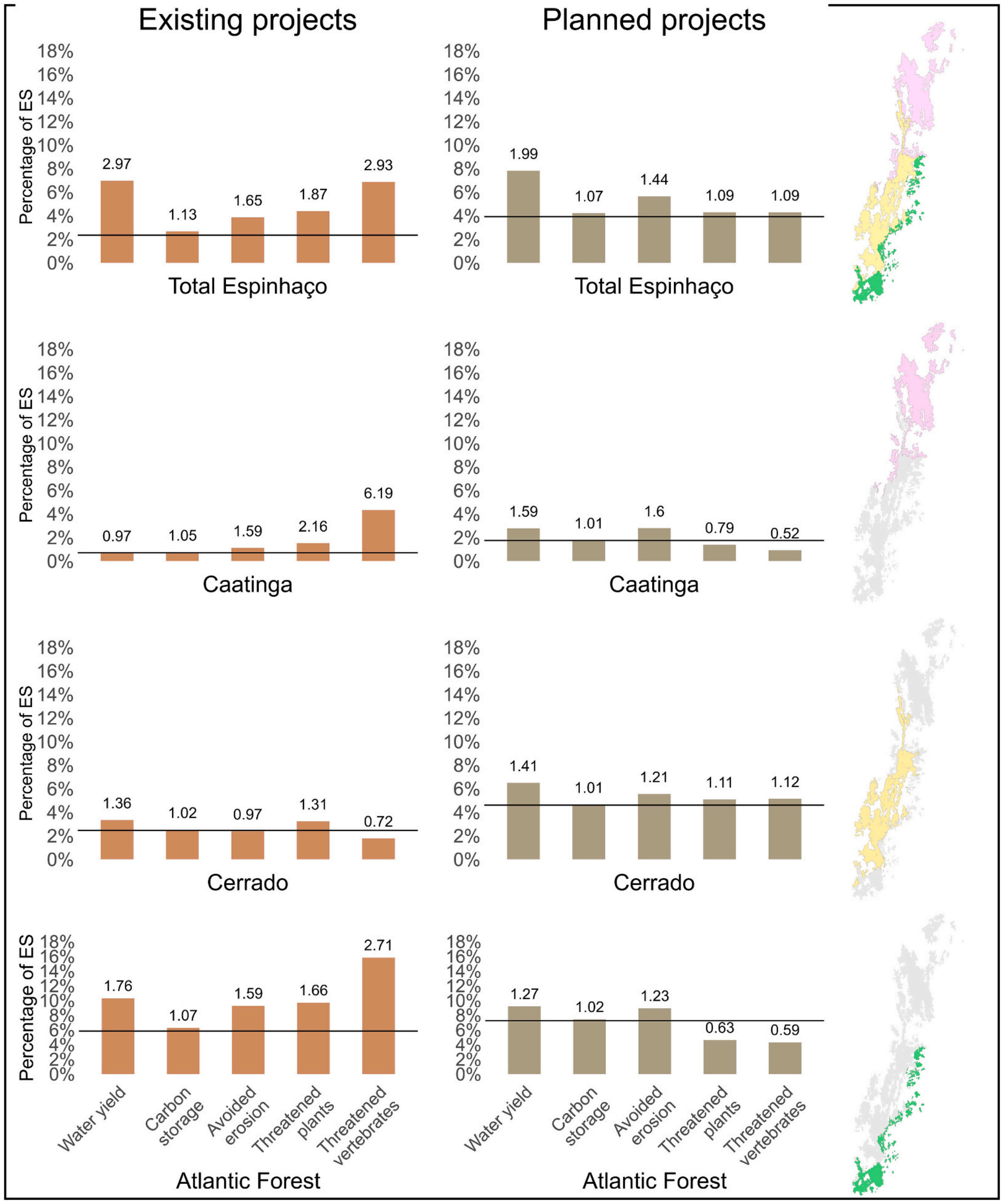

Fig. 4. Percentage of ecosystem services and biodiversity located within existing (pale red) and planned (brown) mining projects across the entire Espinhaço Range and within the Caatinga (pink), Cerrado (yellow), and Atlantic Forest (green). The black horizontal line indicates the percentage of land area occupied by each project category in the whole study area and within each biome. Numbers above the bars show the ratio between the percentage of ecosystem services or biodiversity and the percentage of land area occupied by the projects. Values >1 mean that ecosystem services and biodiversity were overrepresented considering what would be expected for the area of mining projects.

than expected for their area. Furthermore, 69% of planned projects showed ratios >1 for carbon storage than expected for their area. The spatial distribution of these mining projects with high potential impacts on ESs was similar across the two mining categories (existing and planned) but varied by ES type. For water yield, projects with high values (more than two times higher than expected for their area) were predominantly located in the Atlantic Forest portion of the Espinhaço Range (Fig. 5A). The areas targeted for mining contributed significantly to carbon storage and sediment retention and are concentrated in the Cerrado and Atlantic Forest regions (Fig. 5B—C).

Across the entire Espinhaço Range, fewer than 20% of the existing and planned mining projects overlap with the known distributions of threatened plants and vertebrates, likely due to limited sampling of these species in the study area. However, for existing projects, 49% of threatened plant distributions and 55% of threatened vertebrate distributions overlapped areas with ratios greater than three times larger than expected based on their area occupied by the projects. For planned projects, 40% of threatened plants and 48% of threatened vertebrates were associated with ratios greater than three, while small proportions (≤19% of projects) fell into the low ratio classes (1–2 and 2–3) (Figs. 5, S4). Moreover, 30 threatened species (20 plants and 10 vertebrates) had over 30% of their range overlapping with mining projects, suggesting these species are particularly vulnerable to habitat loss caused by mining (Figs. S3, S5, Table S7). Such overlap was more pronounced in the Iron Quadrangle region.

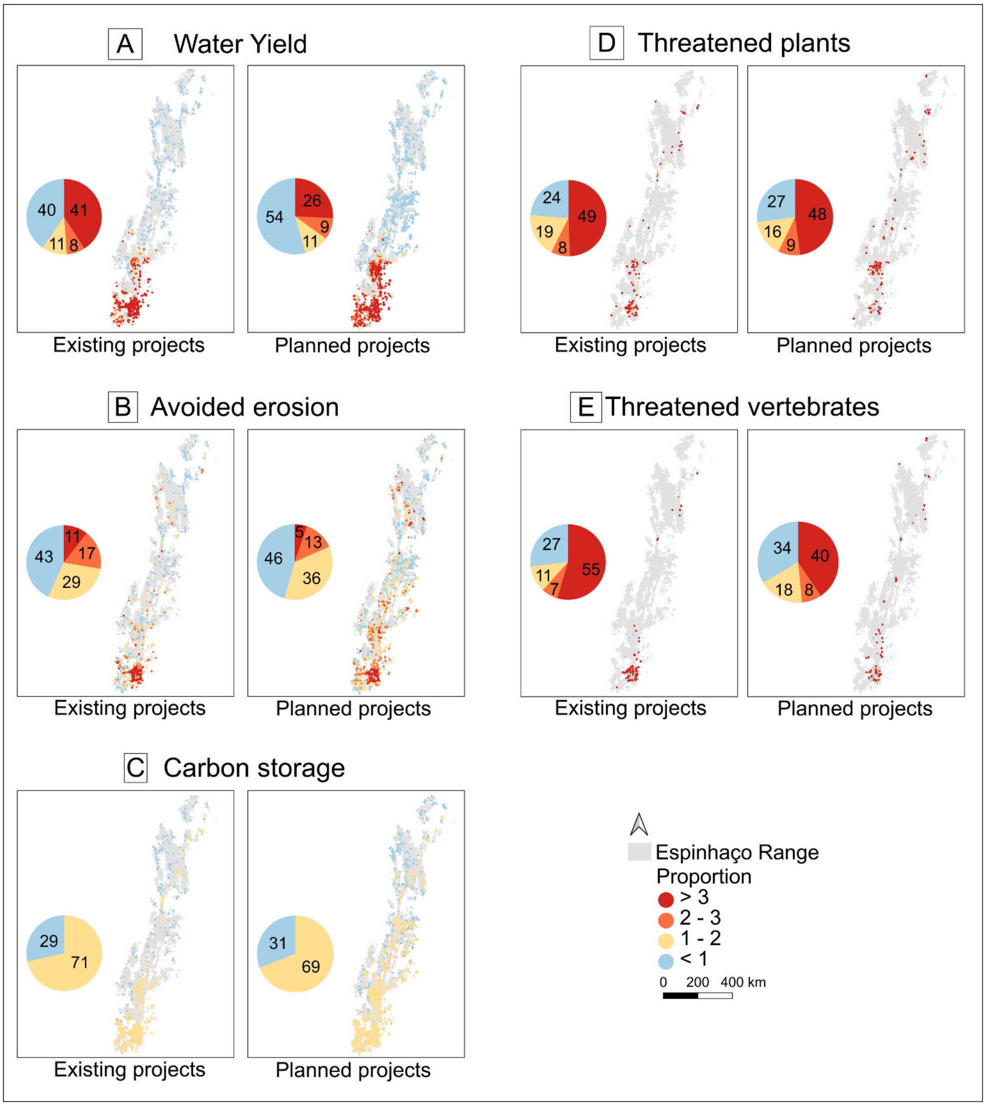

Fig. 5. Proportion of ecosystem services and biodiversity in each area targeted for existing and planned mining projects in the Espinhaço Range. The pie chart shows the percentage of projects whose ratios are higher than expected for the area they occupy within the Espinhaço Range and those whose ratios are lower than expected. Proportions less than one in blue, between one and two in yellow, between two and three in orange, and greater than three in red. Mining projects that do not overlap with the distribution ranges of threatened species were disregarded.

4. Discussion

4.1. *Differential mining impacts on the Espinhaço Range*

Our study is a first attempt to estimate the impacts of mining and quarrying operations on ESs and biodiversity across the entire Espinhaço Range—a region of strategic importance for the mining industry, biodiversity, and the provision of ESs in Brazil (see Fernandes et al., 2020). Both existing and planned mining projects showed high overlap with hotspots for ESs provision across the Espinhaço Range, indicating that mining and quarrying pose a strong impact on water yield and erosion control. The potential impact of mining and quarrying on water yield prevails in existing projects in Atlantic Forest and in planned projects in Caatinga, whereas existing projects in the Caatinga and Atlantic Forest and planned projects in the Caatinga have more potential impact on reducing sediment retention. Finally, the impact of carbon storage is equivalent to that expected from the area of the mining projects. In the planned projects, mining has a relatively lower potential impact than expected, excepting for the Cerrado in the Espinhaço Range.

Quartz, quartzite, and granite mining are expected to expand more extensively in the Espinhaço Range, posing a serious threat to the quartzite ecosystems of *campo rupestre*, while sand mining could double in area. Our estimates of land targeted for mining and quarrying are almost 3-fold previous estimates (Fernandes et al., 2018), but even our results are underestimated considering we have not included infrastructure, and our methods fail to detect small mining operations (Sonter et al., 2023). Although sand mining projects occupy smaller areas than granite or quartzite mining, they usually occur in or near watercourses, leading to significant risks to water quality (Rentier and Cammeraat, 2022). Furthermore, our results are very conservative in relation to the total area of planned projects, since we disregarded projects in the research authorization phase that are within this classification according to Villén-Pérez et al. (2018). These mining projects occupy ~43% of the Espinhaço Range, but their implementation is uncertain, and this stage undergoes feasibility assessments and may or may not proceed (ANM, 2024).

LULCC is required to build and maintain infrastructure supporting mining and quarrying—such as deforestation and plantations (e.g., *Eucalyptus* spp.) (Sonter et al., 2014; Rodrigues et al., 2025). The loss of native vegetation, for instance, leads to increased runoff and reduced base flow (the groundwater contribution to surface streams) (water yield) (Anjinho et al., 2024; Rodrigues et al., 2025). These changes result in higher river flows during wet periods and lower water availability during dry periods (Costa et al., 2003). Our results show that areas targeted for future operations are located in sites important to water regulation, with long-lasting impacts on water security in the Espinhaço Range, especially in the Cerrado, where seasonal rainfall is critical (Uchôa et al., 2024). Such impacts of iron ore mining may be irreversible because the banded iron formations that constitute the aquifers supporting water recharge cannot be restored or fully offset (Silveira et al., 2020).

Despite occupying only 17.3% of the Espinhaço Range, the Atlantic Forest contributes to 54.4% of the total water yield within the range. In contrast, Cerrado does not show significant discrepancies between ESs values and the area it occupies, while the Caatinga contributes the least to this ES, representing 3% of the total water yield. This disparity is likely due to higher rainfall in the Atlantic Forest, which enhances sediment retention, above-ground carbon storage and water infiltration (Anjinho et al., 2024; Rodrigues et al., 2025). It is also necessary to consider the large number of springs in the Cerrado, many of which form extensive rivers, such as the São Francisco River, responsible for supplying water to other biomes (Fernandes et al., 2016). Without adherence to legal requirements and proper ecological restoration, mining expansion in the Espinhaço Range could severely impact the water security of the Atlantic Forest region resulting in profound environmental, energetic and socio-economic consequences (Fernandes et al., 2018, 2020).

The remaining native vegetation within areas targeted for both existing and planned mining projects is over 60%, which presents an opportunity for strategic and assisted conservation efforts. We estimate a potential impact of mining on erosion control of 1.65 times higher than expected by the area of existing projects and 1.44 times higher than expected in planned projects in the Espinhaço Range. In the Caatinga, the impact is ~1.6 times bigger in both project categories. In addition, more than 50% of mining projects are in areas important for sediment retention. Maintaining these areas is essential because native ecosystems play a vital role in retaining sediment, preventing soil erosion, and reducing the intensity of runoff (Gageler et al., 2014). This role in erosion control is supported by other studies, which show that areas with exposed soil are prone to increased erosion (e.g., Anjinho et al., 2024). Mining-related sediment runoff can lead to increased water turbidity, generate acidic aqueous solutions, and introduce pollutants (e.g., Silva et al., 2013) with heavy metals accumulating kilometers downstream, posing a significant threat to aquatic life (Macklin et al., 2023) and communities living in the surrounding lowlands affected by metal mining (Macklin et al., 2023). This risk is especially pronounced in the Atlantic Forest and Caatinga, where both existing and planned mining projects overlap with key areas for sediment retention.

Our analysis of carbon storage relative to the area occupied by existing and planned mining projects is largely underestimated which does not consider the largest carbon pools stored in belowground biomass, such as plant roots and soil fungal mycelia (Terra et al., 2023; Ottaviani et al., 2024) and extensive peatlands (Silva et al., 2023). Biomass in open-canopy ecosystems is concentrated belowground (Hoffmann and Franco, 2003) underscoring the need to consider the potential loss of further carbon storage in the Espinhaço Range due to mining-related LULCC (e.g., road construction and deforestation; Sonter et al., 2017). Such carbon loss undermines climate change mitigation efforts in Brazil (Raihan et al., 2021), compounding the broader environmental risks associated with mining.

The main distinction between the potential impacts of existing and planned mining projects in the Espinhaço Range and its biomes lies in their potential effects on biodiversity. Planned projects exhibit significantly lower relative impacts on biodiversity than expected in relation to the area they occupy, particularly in the Caatinga and in the Atlantic Forest. In contrast, existing projects show high potential impacts on biodiversity for open biomes, with 37% of existing projects and 38% of planned projects expected in savanna, grasslands, and *campo rupestre*. The expansion of operations activities in the Espinhaço Range might largely affect this vegetation and its endemic and threatened biodiversity, especially in the Iron Quadrangle region of the Espinhaço (e.g., Fernandes et al., 2018, 2020; Oswald et al., 2025). This discrepancy can be explained by the concentration of existing projects in the Iron Quadrangle, an area that harbors the highest number of recorded threatened species (see Fernandes et al., 2014, 2018; Pena et al., 2017; Hoffmann et al., 2020).

Our results also reinforce that the expansion of mining will have a pronounced impact on biodiversity of threatened species belonging to plants, reptiles, birds, amphibians, and mammals. The 563 threatened plant species found in the study area indicates that more than one quarter of all threatened plant species in Brazil occur in less than 1% of its territory (see Silveira et al., 2016). While previous studies had already explored the effects of mining on birds and amphibians (Pena et al., 2017; see also Hoffmann et al., 2020), our expanded analyses reveal that plant and vertebrates are likely to be significantly affected (Monteiro et al., 2018), especially in the southeast of the Espinhaço, within the Atlantic Forest domain. The potential impact is even more pronounced for endemic species, as they are more vulnerable to habitat loss when mining projects overlap with their restricted ranges.

Among the species most vulnerable to mining impacts, *L. horizontalis* Chase (Poaceae) and *C. odorata* Linnaeus (Meliaceae), are particularly at risk, with 93% and 76%, respectively, of their distribution range overlapping with existing mining projects (Table S7). In the planned projects, two bat species—*Natalus macrourus* (Gervais, 1855) (Natalidae) and *Furipterus horrens* (F. Cuvier, 1828) (Furipteridae)—both classified as vulnerable (VU), are particularly threatened. *Natalus macrourus* has 87% of its distribution range affected by mining, while *F. horrens* faces 81% overlap. This highlights how mining can significantly reduce the distribution range of threatened species, particularly those with specialized habitat requirements, making them more vulnerable to environmental degradation (Clavel et al., 2011).

4.2. On mining and environmentally sustainable goals

Our findings provide crucial insights for mining companies and public authorities to guide the planning and implementation of effective strategies aimed at mitigating the environmental damage caused by mining in the Espinhaço Range (Fernandes et al., 2020). Although mining projects occupy a relatively small portion of the Espinhaço Range (approximately 2–4%), their potential impact on the unique and low-resilient ecosystems found in this mountaintop region is substantial, perhaps irreversible, but certainly underestimated. The rising global demand for minerals highlights the urgency of reducing the societal dependence on minerals through long-term public–private partnerships that foster recycling, decrease mineral consumption, and promote alternative materials (Giljum et al., 2022).

Although mineral deposits are spatially constrained and mining cannot be arbitrarily relocated, integrating spatial analyses and biodiversity assessments into early planning stages can guide the selection and management of mining sites. For example, prioritizing areas with relatively lower provision of ESs and levels of endemism and threatened species, such as devegetated areas or pastures, where feasible, can help balance economic and conservation goals. Furthermore, society has a fundamental role to play in developing sustainable development strategies (see Moomen et al., 2020) and in pressuring decision-makers to avoid mining in regions of environmental and historical importance, such as the recent conflicts in sites targeted for iron ore mining (see Carneiro et al., 2023). Concomitantly, we recommend the protection of permanent protection areas and legal reserves, as well as expansion of conservation units based on ESs modeling techniques combined with other methodologies in conservation biology. To this end, compliance with legislation is absolutely essential to regulate mining, avoiding illegal extraction, illegal deforestation and socio-environmental conflicts, which may already be in jeopardy in Brazil with bills to approve mining in protected areas (see Villén-Pérez et al., 2018; Siqueira-Gay et al., 2022).

Among the most commonly adopted instruments to reduce the impacts of mining after its implementation are ecological restoration and the subsequent monitoring of degraded areas (e.g., Young et al., 2022). The Brazilian National Environmental Policy, outlined in Law 6.938/1981 (Brazil, 1981) mandates the restoration and improvement of areas degraded by mining. It is critical to integrate scientific knowledge on soil properties, local vegetation, and species reintroduction to effectively meet these obligations (Young et al., 2022). These actions are particularly relevant in light of recent changes to the Brazilian environmental licensing framework. In August 2025, the Brazilian President sanctioned the partial adoption of the Special Environmental License (Brazil, 2021). This legislation allows the establishment of new mining and quarrying operations even in cases of environmental degradation, which may result in an expansion of mining activities in the Espinhaço Range with potential negative implications for ESs and biodiversity (see Fernandes et al., 2025).

4.3. Gaps, challenges, and opportunities

The challenges encountered in modeling ESs for the Espinhaço Range were primarily related to the availability and resolution of biophysical data. For example, we relied on monthly precipitation and reference evapotranspiration data available for the years of 1970 and 2000 period, alongside the 2022 LULC map. Another limitation was the absence of data on evapotranspiration coefficients (Kc) for the different crops and vegetation in climatic regions within the Espinhaço Range. Despite the lack of refined Kc data for Brazil, future studies can estimate it using automated remote sensing techniques, a method suggested by the InVEST (Sharp et al., 2023), though not yet well established in the ESs literature. Additionally, the InVEST model does not account for water previously stored in the soil, such as those in peatlands (Silva et al., 2023), which underestimates the impacts of mining operations on the provision of ESs (Sharp et al., 2023). The lack of high-resolution spatial data required the downscaling of some inputs for InVEST, such as precipitation and reference evapotranspiration (from ~1 × 1 km to 30 × 30 m), above-ground carbon (from 50 × 50 m), and soil organic carbon (from 90 × 90 m). This procedure does not detail local environmental heterogeneity, but it was necessary to harmonize the spatial resolution among datasets. Despite these data and model limitations, we relied on the best available sources in the literature, and our results provide a meaningful qualitative assessment of ESs that should be interpreted on a regional scale.

Regarding biodiversity, a significant challenge arose from the lack of comprehensive sampling for threatened species, which led to many mining projects showing no overlap with species distributions (~80%). This gap likely underrepresents the true impact of mining activities on biodiversity, especially for endemic species with limited distribution or poorly documented populations (e.g., Barbosa et al., 2015). The 2 km buffer zone created around occurrence points to estimate the distribution range of threatened species may underestimate the occurrence of species with a large distribution and overestimate restricted species, but it was not viable to create a species-specific buffer due to the lack of consistent data. Despite this, the general buffer zone allows for a standardized and conservative estimate of the potential impacts of mining on all taxa, which is appropriate for a regional-scale assessment. Finally, we strongly recommend the development of more baseline studies focused on the biodiversity of the Espinhaço Range, especially increasing sampling efforts of threatened and endemic species whose geographic ranges are not well-represented in databases. In addition, data on species ecological niches and belowground carbon storages would also provide a more robust foundation for future estimates of loss of ESs and threatened species. By improving the quality and breadth of biophysical and biodiversity data, refined models incorporating infrastructure supporting mining and quarrying will better predict the environmental impacts for humans and nature. Due to the extreme importance of the Espinhaço Range for biodiversity and water security in Brazil, these efforts should be used to guide more informed decision making and more effective mitigation and conservation efforts in the Espinhaço Range as a whole, both in mining areas and in conservation units, farms, and other areas.

5. Conclusions

This study highlights the critical role of the Espinhaço Range in Brazil in water security, erosion control, and carbon storage, and supporting threatened biodiversity across the Cerrado, Atlantic Forest, and Caatinga biomes. Significant overlap of existing and planned mining projects with priority areas for conservation indicate potential land use conflicts and demands public policies to avoid and mitigate future socio-environmental impacts. Our results provide useful insights for both public authorities and mining companies to prioritize, for example, areas for preservation and environmental compensation.

This study faced limitations due to the lack of detailed, high-resolution climate and biophysical data, as well as crop evapotranspiration coefficients for natural ecosystems, which may have led to underestimations of water-related ESs. In addition, the lack of publicly available information on sampling of threatened species likely means that the potential impacts of mining on biodiversity are greater than those found here. Despite these limitations, the results provide a meaningful qualitative impact of mining on ESs and biodiversity.

Integrating environmental specificities into mining strategies can also benefit the mining sector by reducing environmental impacts, strengthening corporate social responsibility and aligning with national and international sustainability commitments. Mining companies focusing on areas with lower ESs provision and lower biodiversity than in more sensitive and complex ecosystems and allocating resources to high standard ecosystem restoration, can improve social acceptance and relations with local communities, and can mitigate operational risks such as water loss, soil erosion and increased carbon emissions.

CRediT authorship contribution statement

Kleber F.A. da Silva: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Leila Meyer:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Fernando M. Resende:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Fernando A.O. Silveira:** Conceptualization, Methodology, Visualization, Writing – review & editing. **G. Wilson Fernandes:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used OpenAI's ChatGPT4.0 in order to improve language. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2026.181479.

Data availability

We provide the link with our data and codes in the attach file step a short embargo period.

Scripts and data (Original data) (Figshare)

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