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Geodiversity and abiotic ecosystem services in parks from the far north of Minas Gerais: educational and geotourism potential

Geodiversidade e serviços ecossistêmicos abióticos em parques estaduais do extremo norte de Minas Gerais: potencial educacional e geoturístico

Geodiversidad y servicios ecosistémicos abióticos en parques del extremo norte de Minas Gerais: potencial educativo y geoturístico

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Abstract

The state parks from the far north of Minas Gerais are strategic for raising society's awareness about the importance of nature. Considering that in the State Parks of Montezuma, Caminho dos Gerais (PECGerais), and Serra Nova e Talhado (PESNT), there are important abiotic ecosystem services, geodiversity must be incorporated into environmental interpretation activities. In this work, sites intended for public use were evaluated regarding their educational and touristic potential related to geodiversity and the degradation risk. Geosites and geodiversity sites were selected in which geological processes can be approached by weaving relationships with biodiversity and cultural aspects to encourage visitors to have a holistic view of nature. These sites also encourage discussion on various Sustainable Development Goals – SDGs. Considering that they are located in a region with a semi-arid climate and that these parks are essential for the water supply in their surroundings, aspects related to water resources are of great relevance and may unequivocally be addressed in all selected sites, especially in the Talhado Canyon (PESNT), Gameleiras Dam (PECGerais) and in the Lagarto Rock (PEM). The intrinsic relationship between geodiversity and biodiversity is observed at the Peatlands of Gerais Santana (PESNT), Vereda das Piranhas Trail (PECGerais) and the Lavra Trail (PEM) sites. The relationship between geodiversity and cultural aspects of the region are evident in all selected sites. The high educational and geotourism potential, associated with the low degradation risk, indicates that all these sites are useful for public use activities.

Keywords: Geoheritage. Espinhaço Range. Public use. Environmental Education. Sustainability.

Resumo

Os parques estaduais do extremo norte de Minas Gerais são estratégicos para conscientização sobre a importância da natureza. Considerando que nos parques Estaduais de Montezuma (PEM), Caminho dos Gerais (PECGerais) e Serra Nova e Talhado (PESNT) existem importantes serviços ecossistêmicos abióticos é fundamental que a geodiversidade seja incorporada às atividades de interpretação ambiental. Neste trabalho, locais destinados ao uso público foram avaliados quanto ao seu potencial educacional e turístico relacionados à geodiversidade, bem como ao risco à degradação. Foram selecionados geossítios e sítios da geodiversidade em que processos geológicos podem ser abordados tecendo relações com a biodiversidade e aspectos culturais, de modo a estimular nos visitantes uma visão holística da natureza. Tais pontos propiciam também a discussão sobre diversos Objetivos do Desenvolvimento Sustentável – ODS. Considerando que se situam em uma região de clima semiárido e que estes parques são imprescindíveis para o abastecimento de água do seu entorno, aspectos relacionados aos recursos hídricos são de grande relevância e podem inequivocamente ser abordados em todos os pontos selecionados, especialmente no Cânion do Talhado (PESNT), Barragem de Gameleiras (PECGerais) e na Pedra do Lagarto (PEM). A intrínseca relação entre geodiversidade e biodiversidade é observada nos pontos Turfeiras do Gerais Santana (PESNT), Vereda das Piranhas (PECGerais) e Trilha da Lavra (PEM). A relação entre a geodiversidade e aspectos culturais é evidente em todos os pontos selecionados O elevado potencial educacional e geoturístico, associado ao baixo risco à degradação indica que todos os locais são úteis às atividades de uso público.

Palavras-chave: Geopatrimônio. Serra do Espinhaço. Uso public. Educação Ambiental. Sustentabilidade.

Resumen

Los parques estaduales del extremo norte de Minas Gerais son estratégicos para generar conciencia sobre la importancia de la naturaleza. Considerando que en los Parques de Montezuma (PEM), Caminho dos Gerais (PECGerais) y Serra Nova e Talhado (PESNT) existen importantes servicios ecosistémicos abióticos, es fundamental que la geodiversidad sea incorporada en las actividades de interpretación ambiental. En este trabajo se evaluaron lugares destinados al uso público en cuanto a su potencial educativo y turístico relacionado con la geodiversidad, así como el riesgo de degradación. Se seleccionaron geositios y sitios de geodiversidad en los que se puedan abordar procesos geológicos tejiendo relaciones con la biodiversidad y aspectos culturales, con el fin de incentivar a los visitantes a tener una visión holística de la naturaleza. Estos puntos también fomentan la discusión sobre varios Objetivos de Desarrollo Sostenible - ODS. Teniendo en cuenta que se encuentran en una región de clima semiárido y que estos parques son esenciales para el abastecimiento de agua en su entorno, los aspectos relacionados con los recursos hídricos son de gran relevancia y pueden inequívocamente ser abordados en todos los puntos seleccionados, especialmente en el Cañón del Talhado (PESNT), en la Presa de Gameleiras (PECGerais) y en la Piedra del Lagarto (PEM). La relación intrínseca entre geodiversidad y biodiversidad se puede discutir en los puntos Turberas del Gerais Santana (PESNT), Sendero Vereda das Piranhas (PECGerais) y Sendero de la Lavra (PEM). La relación entre la geodiversidad y los aspectos culturales se puede discutir en todos los puntos seleccionados. El alto potencial educativo y geoturístico, asociado al bajo riesgo de degradación, indica que todos los lugares son útiles para actividades de uso público.

Palabras-clave: Geopatrimonio. Sierra del Espinhaço. Uso público. Educación Ambiental. Sostenibilidad.

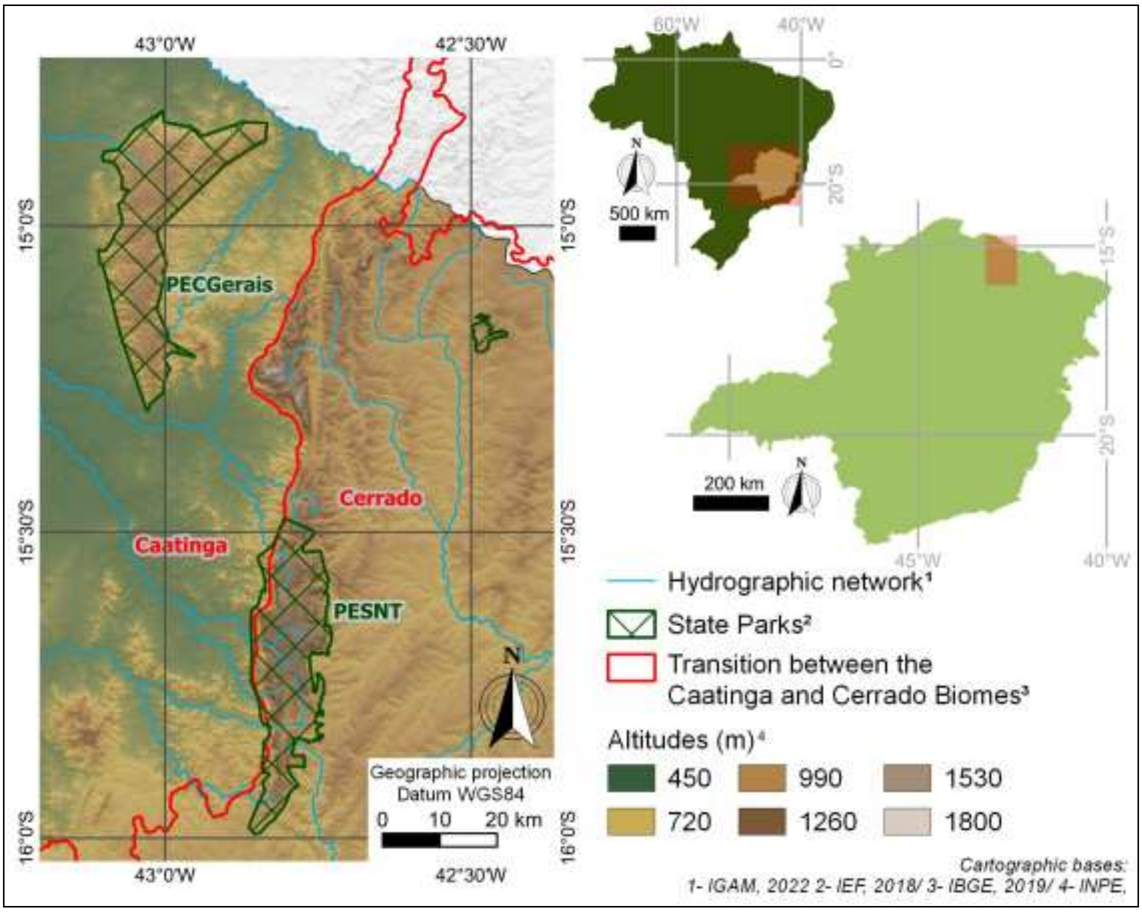
Introduction

Environmental impacts resulting from human actions and the effects of climate change have prompted society to reflect on its relationship with nature. International and national institutions have fostered initiatives aimed at mitigating the degradation of ecosystems and promoting a more harmonious relationship between society and nature (Gill, 2017; Schrodt et al., 2019; Crofts et al., 2020; Gill, 2021). The publication of the Sustainable Development Goals – SDGs of the 2030 Agenda by the United Nations(UN, 2015) is considered an important step, as it lists specific points that need to be worked on together. Although the challenges are many, it is imperative that people understand the dynamics of ecosystems and processes associated with them. Considering that nature is one, and that generally the abiotic components (geodiversity) are less known than the biotic (biodiversity) by the general population, additional efforts need to be made to reverse this lapse.

The relationship between geodiversity and the SDGs has been widely discussed (Brilha et al., 2018; Reynard and Brilha, 2018; Gill and Smith, 2021; Gray and Crofts, 2022; Araujo et al., 2022), as well as the need for the participation of geosciences for the effective awareness of society (Mora, 2013; Crofts, 2018). The importance of protected areas in this task is unquestionable. Considering that interpretative activities are usually focused on aspects of biodiversity, it is necessary to incorporate geodiversity into public use activities (Crofts et al., 2020; Mucivuna et al., 2022a; Mucivuna et al., 2022b Gordon et al., 2021).

The north of Minas Gerais, a region of low HDI and semi-arid climate, has important conservation areas in the Central Espinhaço Range (Danderferer Filho, 2000), whose creation is due not only to the protection of biodiversity, but to the conservation of water resources. Specifically, the three northernmost state parks, Serra Nova e Talhado State Park – PESNT, Montezuma State Park – PEM and Caminho dos Gerais State Park – PECGerais (Figure 1) are essential for the water supply of several municipalities in the region, corresponding to a population of more than 150,000 inhabitants.

Figure 1. Digital model of the terrain with the location of the three state parks studied and the limit that marks the transition between the Caatinga and Cerrado biomes in the far north of Minas Gerais



Source: Authors, 2023.

The Espinhaço Range represents not only a water divide, but also marks the transition between the Cerrado and Caatinga biomes (IBGE, 2019). There are also fragments of Atlantic Forest and high endemism in the *campos rupestres* (rupestrian grasslands), which increases the region's relevance from the point of view of biodiversity. The parks studied are part of both the Espinhaço Range Biosphere Reserve – RBSE and the Atlantic Forest Biosphere Reserve – RBMA.

The parks have great potential for interpretative activities. There are several geosites and geodiversity sites (Brilha, 2016), conducive to addressing the current and ancient processes of Planet Earth. Many of these sites are also excellent for addressing both the intrinsic value of geodiversity and the relationship between biodiversity and geodiversity. They are also useful to discuss the goods and services provided by geodiversity to society, that is, the ecosystem services related to geodiversity, also called abiotic ecosystem services (Gray, 2011; Gray, 2013; Alahuhta et al., 2018; Garcia, 2019). Thus, this paper aims to select places to carry out educational activities and promote geotourism that provide an integrated view of nature, with content that adds abiotic, biotic and cultural aspects.

Geological Context

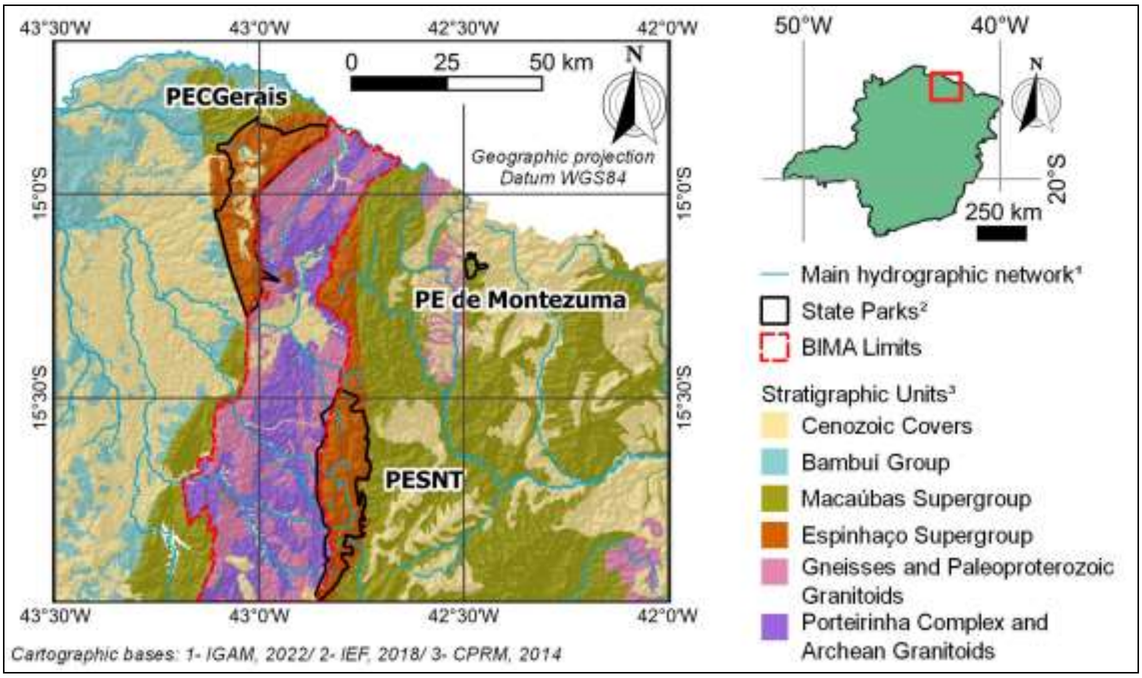
The geological evolution of the region where the studied parks are located is complex, comprising events from the Archaean to the Cenozoic (Figure 2). The last large-scale geotectonic event that affected the region was the Brasiliano Orogeny, so the region falls within the context of the Araçuaí Orogen, close to the limit of the São Francisco Craton (Danderfer Filho, 2000; Pedrosa-Soares et al., 2007). The oldest rocks correspond to the Itacambira-Monte Azul Block – BIMA, which is formed by TTG gneisses from the Porteirinha Complex and Archean to Paleoproterozoic intrusive granitoids.

The orthogneisses of the Porteirinha Complex formed during the processes of stabilization of the continental crust in the Archean, whose recrystallization ages date back to 3,300 Ma (Silva et al., 2016; Bersan, 2019). Granitoids, formed in a late-orogenic to post-collisional context, are related to the consolidation of the Paleocontinent São Francisco-Congo, between the end of the Archean and the beginning of the Paleoproterozoic (Bersan et al., 2018). Rocks from the BIMA are abundant in the vicinity of the studied parks and are present only in a small area of the PESNT and PECGerais.

After a period of tectonic stability, the paleocontinent São Francisco-Congo underwent successive rifting events, between the Paleoproterozoic and the Neoproterozoic (Danderfer Filho et al., 2009; Costa et al., 2017; Costa et al., 2018). These extensional processes led to the deposition of thick sedimentary packages, corresponding to the rocks of the Espinhaço and Macaúbas Supergroups (Costa & Danderfer Filho, 2017; Souza, 2019). These are the largely dominant units in the three parks, whose sedimentation is related to varied depositional settings and paleoclimatic conditions.

The closure of the Macaúbas Basin started in the Neoproterozoic and caused extensive deformation and metamorphism of the sedimentary packages, conditioned by pre-existing geological structures and basement blocks. This compressional tectonics, related to the Araçuaí Orogen, in addition to generating large-scale reverse faults, caused the metamorphism, folding, uplift and tilting of the sedimentary strata (Bersan, 2015; Bersan et al., 2017), which represent the initial stages of the Espinhaço Range formation.

Figure 2. Simplified geological map of the region where Serra Nova e Talhado State Park, Montezuma State Park and Caminho dos Gerais State Park are located



Source: Authors, 2023.

Methodology

In order to select geosites and geodiversity sites, consultations were made with the civil servants of the State Institute of Forests – IEF, and field activities were carried out in areas where public use is currently taking place or may potentially be designated for public use in the future. The points and trails visited, which are interesting from a geodiversity perspective, were evaluated both qualitatively and quantitatively regarding their scientific value, potential for educational and geotourism use, and risk of degradation, following the methodology outlined by Brilha (2016). The GEOSSIT - Geosites and Geodiversity Sites Registration and Quantification System, developed by the Geological Survey of Brazil – CPRM, was used, with minor modifications made to the methodology to adapt it to the Brazilian context. The GEOSSIT was created with the objective of facilitating the quantitative assessment of geosites and geodiversity sites throughout Brazil and contributing to the development of the national geological heritage inventory (Lima et al., 2012).

Two points were selected in each park to be prioritized in environmental education and geotourism activities. Special attention was given to places where, in addition to aspects related to geological events, other associated interests occur. More specifically, we sought places where abiotic ecosystem services could be observed or discussed, and also the relationship between geodiversity and biodiversity, as well as their cultural implications.

The identification and discussion of abiotic ecosystem services is based on the work of Gray (2013). The author's proposal aims to align with the methods already employed for the assessment of biodiversity, similar to the Millennium Ecosystem Assessment (MA, 2005), which categorizes ecosystem services into four categories: regulation, support, provision, and cultural. And it inserts a fifth category, knowledge services.

Geodiversity and Ecosystem Services

The three parks have excellent outcrops to observe aspects related to Brasiliano Orogeny. The rocks, whose layers dip to the east, at moderate to subvertical angles, also exhibit folds of different dimensions and geometries, which can be perceived by visitors and students of all levels of education. In addition, the low metamorphic degree (green shale facies) generally allows features of the sedimentary protolith to be observed.

In addition to understanding geological processes and tectonic environments, many of these sites also allow us to observe or discuss abiotic ecosystem services. In common, supporting service of *platform for human activities* and *habitat provision*;

provisioning service of *food and beverage*; and cultural service of *environmental quality* can be mentioned (Table 1).

Table 1. Abiotic ecosystem services identified in the areas of the Serra Nova and Talhado State Parks; Caminho dos Gerais and Montezuma; based on Gray (2013)

	Regulating	Supporting	Provisioning	Cultural
PESNT	***Terrestrial processes*:** carbon storage (peatlands)	***Habitat provision*:** Biosphere Reserve, rupestrian grasslands; transition between Cerrado and Caatinga biomes; ***Platform for human activities:*** Construction of dam (geological structures); ***Burial and storage:*** recharge of aquifers	***Food & Drink*:** capturing water from drainage systems.	***Environmental quality:*** landscape, water courses and waterfalls ***Cultural, spiritual and historical significance*:** landscape, drovers, religious importance; recreation and tourism
PEM	***Water quality regulation:*** purification of chemicals used in silviculture	***Habitat provision:*** Biosphere Reserve; ***Platform for human activities:*** Construction of dam (geological structures); ***Burial and storage:*** recharge of aquifers	***Food and drink*:** water capture from drainage systems; ***Ornamental products*:** old amethyst mine	***Environmental quality:*** landscape, Cerrado fruit collection
PECGerai s		***Habitat provision:*** Biosphere Reserve ***Platform for human activities* s:** Dam construction (geological structures) ***Burial and storage:*** recharge of aquifers	***Food and drink*:** water capture from drainage systems	***Environmental quality:*** landscape, centennial path, recreation, Cerrado fruits collection

Source: Authors, 2023.

Regarding supporting services, the *platform-type service for human activities* refers to geological structures that enabled the construction of dams that ensure water supply to municipalities adjacent to the parks, as well as plateau areas previously used for forestry and livestock (IEF 2020; IEF, 2023a). The *habitat provision* service is related to metasedimentary rocks and variations in relief and altitude, which allowed the adaptation of species, many of them rare and endemic. Examples include rupestrian grasslands and different Cerrado phytophysiognomies, which occur at the highlands.

The relief also favored the protection of the biota against anthropogenic activities, as they are generally less impacted than adjacent areas of lower altitude. The plateau areas of the three parks represent important recharge areas of the aquifers and, therefore, also provide the supporting service of the *burial and storage* type.

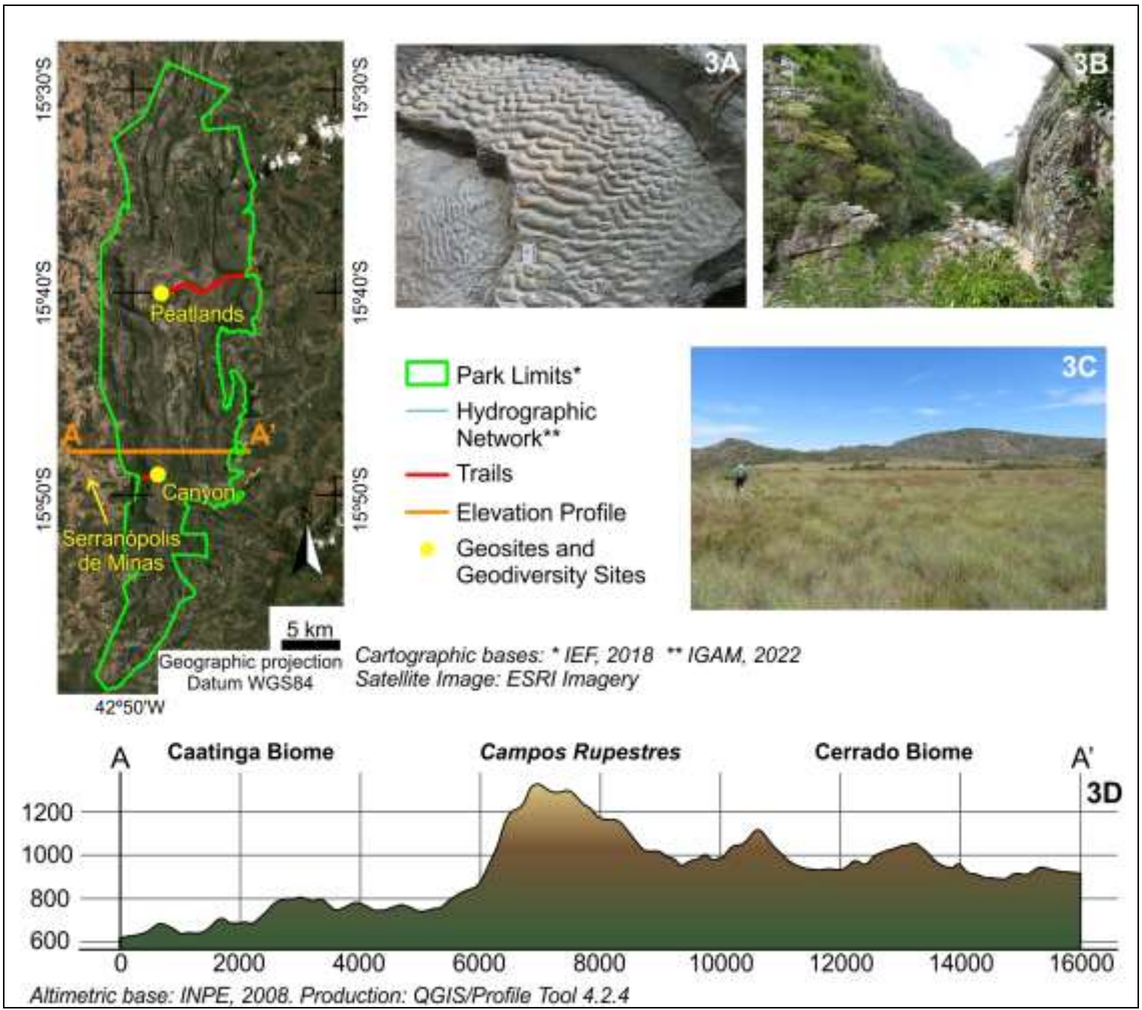
One of the main services provided by the parks refers to the supply of water to the population, characterizing a *food and beverage* provisioning service. In the three parks, there are springs that supply dams: Mosquito River Dam (PESNT), Gameleiras Dam (PECGerais) and Montezuma Dam (PEM). It is common to find pipelines in the rivers and waterfalls of the three parks, which serve as a direct water capture for communities in the surrounding areas. Inside the parks, important tributaries of the Pardo River, São Francisco River, and Jequitinhonha River Basins also originate.

As for cultural services, the three parks provide *environmental quality* services, largely related to beautiful landscapes, rivers, and waterfalls. Other geological characteristics and ecosystem services, specific to each park, deserve to be discussed specifically.

Serra Nova and Talhado State Park – PESNT

The PESNT (Parque Estadual Serra Nova e Talhado) was created in 2003, with an original area of 12,658.298 hectares (Figure 3). The park was expanded in 2008 to occupy an area of 49,890,619 ha. It is located in a region where the Cerrado and Caatinga biomes occur, with enclaves of Atlantic Forest. The altitude ranges from 550 m to 1550 m. The lowest elevations occur in the western portion of the park, and correspond to the transition between the Cerrado biome and the Caatinga, the latter occupying the lower areas to the west. The park protects at least 50 springs. Among the parks studied, it is the most advanced in terms of public use. In addition to environmental education activities, it is open to visitors. The Management Plan, approved in 2019, mentions the existence of 28 cataloged attractions, but only 5 are structured for public use (IEF, 2020). The Public Use Plan is under preparation.

Figure 3. Limits of Serra Nova and Talhado State Park, with the location of the selected points. 3A – Wave marks in quartzite found on the trail that cuts through the Talhado Canyon, related to a marine deposition environment; 3B – Interior of the Talhado Canyon, at the height of Gruta da Santa; 3C – Section of the trail that crosses the Gerais Santana, where peatlands occur. 3D – Elevation profile A–A' (orange line) that illustrates the relationship between altitude and the transition between the Caatinga biome (to the west) and the Cerrado biome (to the east)



Source: Authors, 2023.

Chaves et al. (2009) and Egger (2006) studied the rocks of the Espinhaço Supergroup of the region that covers the PESNT and proposed a division into five stratigraphic units that would correspond, from the base to the top, to marine, fluvial, coastal aeolian and desert aeolian depositional environments. The stratification and dip of the rock layers are widely observable characteristics in the park area. Weathering and erosion processes that lead to the development of ruiniform relief can also be observed in the upper stratigraphic units. Concerning the preserved sedimentary structures, it is worth highlighting the ripple marks related to marine environments (Figure 3A) and the large-scale cross-bedding structures in units corresponding to aeolian environments.

In the PESNT, the selected points were the Talhado Canyon (Figure 3B), starting from Serranópolis de Minas to the Gruta da Santa (2.6 km round trip), and the peatlands of Gerais Santana, which occur in a segment of the Serra Nova Hiking Trail - Gerais Santana, originating from the headquarters of PESNT in the district of Serra Nova, Rio Pardo de Minas. The peatlands are best observed after approximately 9 km of the trail (18 km round trip).

The Talhado Canyon, which has its origin related to a normal fault, represents the only complete stratigraphic cross-section of the Espinhaço Supergroup in northern Minas Gerais (Chaves et al., 2009). Right at the beginning of the trail, you can find metavolcanosedimentary rocks from the basal unit of the Espinhaço Supergroup in the region. Continuing along the trail, there are quartzites related to a shallow marine depositional environment, where ripple marks are abundant. The canyon controls the course of the Mosquito River, one of the main perennial rivers in the region. The cliffs expose a variety of brittle structures (faults and fractures) that influence the infiltration of water and maintain the perennial flow of the river. Gruta da Santa is the ideal place to observe these structures. The Mosquito River provides an important ecosystem service for water supply. In addition to direct water capture for the surrounding communities, the river feeds a dam adjacent to the park that supplies a significant portion of Serranópolis de Minas and neighboring municipalities with water.

The canyon is also culturally important in many ways. It represents a traditional path of "*tropeiros*" (drovers), who brought food grown in the region of the *"gerais"* to the Caatinga. It is also a place of pilgrimage, to where there is an image of Our Lady of Aparecida. Regarding historical events, the canyon was one of the possible places where the Miguel Costa Prestes Column would have passed, in the maneuver called the Hungarian Loop, when fleeing from loyalist troops, at the beginning of the twentieth century (Carmo and Kamino, 2015). The significance of the Talhado Canyon is recognized by the Brazilian Commission on Geological and Paleobiological Sites, and it is included in Volume II of the publication "Geological and Paleontological Sites of Brazil" (Chaves et al., 2009).

The Peatlands of Gerais Santana point was chosen primarily for its importance related to ecosystem services (Table 2). However, at the beginning of the trail, outcrops of quartzite are observed with moderate dip (Sn 350/40). In the highlands, pedogenetic processes can be discussed because in the rupestrian grasslands, there are Quartzarenic Neosols adjacent to the peatlands, which represent Organic Soils.

Peatlands are important because they perform various abiotic ecosystem services. Regarding water resources, they are essential for storing large volumes of water and regulating the flow of watercourses (Silva, 2022). The water continuously released in the plateau areas percolates the fractured quartzite aquifer and guarantees the continuity of several streams and rivers.

Another aspect is related to carbon storage, characterizing an important ecosystem regulating service. The *Earth history* type of knowledge service can also be mentioned, related to the paleoenvironmental evidence of the Quaternary Period. Paleoclimatic studies have been conducted in the peatlands of the Southern Espinhaço, providing information about climatic variations up to 34,000 years ago (Silva and Silva, 2017; Silva et al., 2020). It is important that these studies also extend to this portion of the Espinhaço Range. Considering that studies have not yet been conducted in these peatlands, it can be concluded that this is a potential ecosystem service.

Peatlands can also provide another knowledge ecosystem service, such as *environmental monitoring and prediction*. According to Silva et al. (2022), the water quality in peat bogs provides evidence of the degree of degradation of these ecosystems. Given that before the creation of PESNT, the areas where peatlands occur were used for livestock, geochemical monitoring of the water can provide essential information about the environmental recovery of these ecosystems. The same authors state that fluctuations in the water table level can degrade peatland ecosystems, so this monitoring will also help estimate the impact of climate change in the region.

In accordance with the quantification methodology proposed by Brilha (2016), the Talhado Canyon is considered a geosite due to its scientific significance. It also has great educational and touristic potential and a low risk of degradation. As the Peatlands of Gerais Santana has not been the subject of scientific studies, it is classified as a geodiversity site. However, it has great educational and tourist potential, and low risk of degradation. Therefore, the two points are suitable for carrying out public use activities (Table 2).

Table 2. Abiotic, biotic and cultural aspects of interest and quantitative assessment of the geodiversity of the Serra Nova and Talhado State Park points selected for educational and geotourism activities. SV – Scientific Value; EP – Educational Potential; TP – Tourist Potential; RD – Risk of Degradation. Coordinates in UTM.

	Abiotic Aspects	**Biotic Aspects**	**Cultural Aspects**	**Quantification**
Talhado Canyon **(734308 E / 8250147 S)**	Sedimentary structures; Tilted layers and metamorphic foliation; Percolation of water by brittle structures; Normal fault that controls canyon formation	Large vegetation associated with perennial drainage (riparian forest); Fauna	Water collection for surrounding communities; Tropeiros Path; Image of Our Lady Aparecida (Gruta da Santa); Passage of the Miguel Costa Prestes Column; Leisure	SV: 260 (Geosite) EV: 295 TV: 240 RD: 65
Peatlands of Gerais Santana **(734818 E / 8266651 S)**	Quartzarenic Neosols; Peatlands (Organosols); Springs	Rupestrian grasslands; Fauna	Traditional communities (Geraizeiros)	SV: 160 (Geodiversity Site) EP: 280 TP: 205 RD: 70

Source: Authors, 2023.

Montezuma State Park – PEM

Montezuma State Park (Figure 4), created in 2007, represents the smallest state park in Minas Gerais with an area of 1,743.2060 ha (IEF, 2023b). The park presents contrasts in relation to public use. If, on the one hand, environmental education activities have been carried out at least since 2016, on the other hand, tourist activities are allowed only with authorization and monitoring by the IEF. The preparation of the Management Plan is scheduled for 2023.

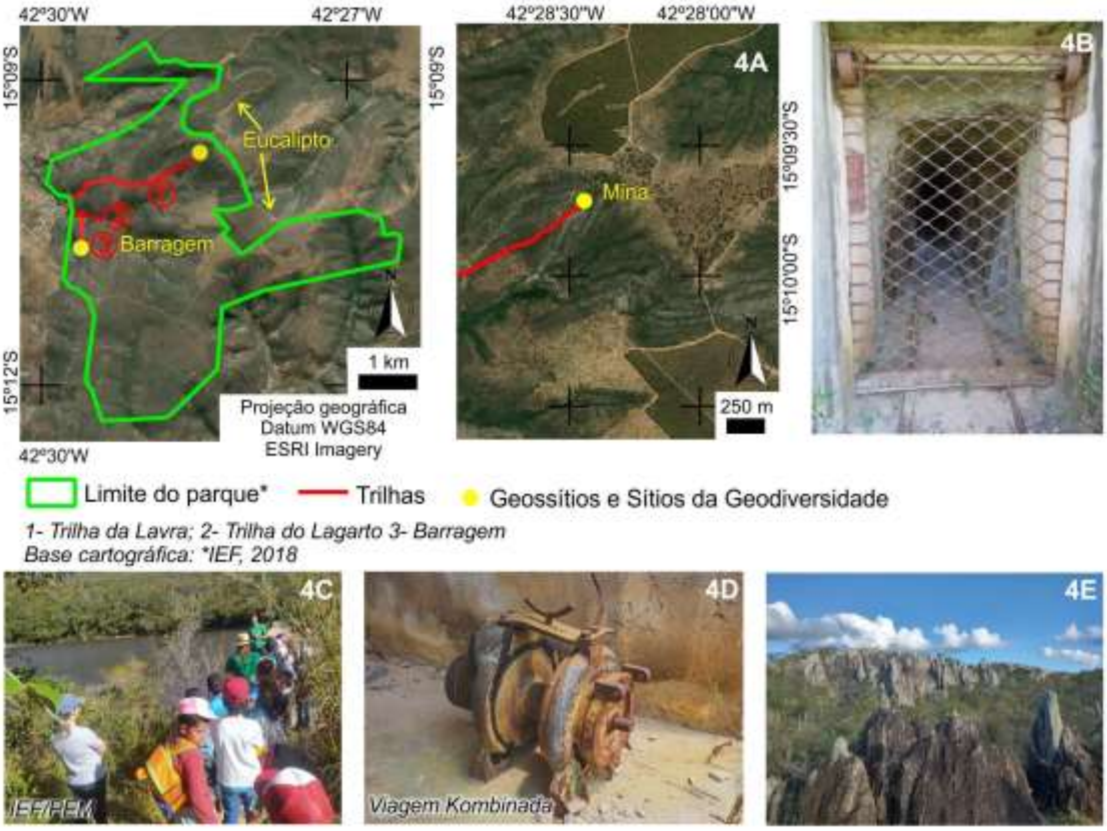
In the park, there are quartzites and metaconglomerates from the Macaúbas Supergroup, near the contact with Paleoproterozoic gneisses and granitoids. The sedimentation corresponds to the first Neoproterozoic continental extension event in the region, characterized by a continental to shallow marine depositional environment.

The points chosen from the PEM are: Amethysts of Montezuma and Lagarto Rock. The first corresponds to facilities of an underground mine (Figure 4A), which operated from 1936 to 2007. The point is reached through the Lavra Trail, a hiking trail 6.3 km long (round trip). The old mine stands out for its geotourism potential. There are still remnants of the project's facilities and machinery, as well as a large amount of amethyst crystals in the tailings piles. A peculiarity of the deposit is that the amethyst, of the prasiolite variety, acquires a bluish or greenish color, upon heat treatment or irradiation. The mineralization is characterized by a swarm of veins with a thickness of up to 2 meters, whose main orientation coincides with the hinge zone of an isoclinal fold, which has been disrupted (Dias et al., 2019) (Figure 4B).

Aspects related to mineralization, petrogenesis, sedimentary environments, structural geology, and tectonic events can be discussed with visitors because the subverticalized layers (Sn 238/70) of one of the fold's limb are well-exposed along the trail before reaching the mine. From there, the water dam that supplies the municipality can be seen (Figure 4C).

The second point, Lagarto Rock, is reached after walking about 950 m of the Lagarto Trail (1.9 km round trip), where good rock exposures occur, both of quartzites and metaconglomerates. Right at the beginning, the trail crosses a drainage. At other points, but especially at Lagarto Rock, there is an excellent view of the old mine and several drainages. There is also the eucalyptus plantation in the plateau areas, upstream of the springs, as well as the Cerrado vegetation, now under regeneration. This Vegetation is essential for maintaining the livelihoods of traditional communities, the Geraizeiros. At Lagarto Rock there are also Quartzarenic Neosols and laterites covering metaconglomerates, in addition to the ruiniform relief that develops on the metasedimentary rocks (Figure 4E). As it is a shorter trail, it can be extended to the water dam, increasing the route by 850 m (round trip).

Figure 4. Limits of Montezuma State Park, with the location of the selected points. 4A – Enlarged satellite image highlighting folded rocks and the location of the old mine; 4B – Entrance to the underground amethyst mine; 4C – Environmental education activities conducted by IEF staff at Montezuma Dam; 4D – Remaining machinery that was vandalized; 4E – Quartzite ridges with subvertical foliation observed from Trilha do Lagarto



Source: Authors, 2023.

In both trails, in addition to the supporting, provisioning, and cultural services listed in Table 1, it is worth highlighting the possibility of addressing the provisioning service related to *ornamental products*, provided by the old amethyst mine. A variety of aspects related to non-renewable resources can be discussed, including their rarity and the complexity of their formation, environmental impacts resulting from their extraction, as well as their growing demand by society.

The Amethysts of Montezuma Point is considered a geosite, according to the methodology of Brilha (2016) (Table 3). The scientific importance refers to the characteristics of the amethyst, which is of the prasiolite variety. The Lagarto Rock

Point is considered a geodiversity site. The two points have similar educational and geotourism potential. However, the risk of degradation is higher at the Ametistas de Montezuma point, which requires greater attention in the planning of public use activities.

Table 3. Abiotic, biotic and cultural aspects of interest and quantitative assessment of the geodiversity of the Montezuma State Park points selected for educational and geotourism activities. SV – Scientific Value; EP – Educational Potential; TP – Tourist Potential; RD – Risk of Degradation

	Abiotic aspects	Biotic Aspects	Cultural Aspects	Quantification
Amethysts de Montezuma **(771385 E / 8322146 S)**	Subvertical foliation (fold limb). Amethyst mineralization; Aquifer recharge areas and drainage systems.	Cerrado Vegetation	Traditional communities (Geraizeiros) Heritage of Minas Gerais	SV:230 (Geosite) PE: 270 TP: 240 RD: 205
Lagarto Rock **(769360 E / 8320499 S)**	Conglomerates and sandstones; Laterites; Subvertical foliation; Ruiniform relief (crests); Silviculture in water recharge areas	Cerrado Vegetation; Impacts of silviculture	Traditional Communities; Leisure	SV: 160 (Geodiversity Site) PE: 295 TP: 235 RD: 100

Source: Authors, 2023.

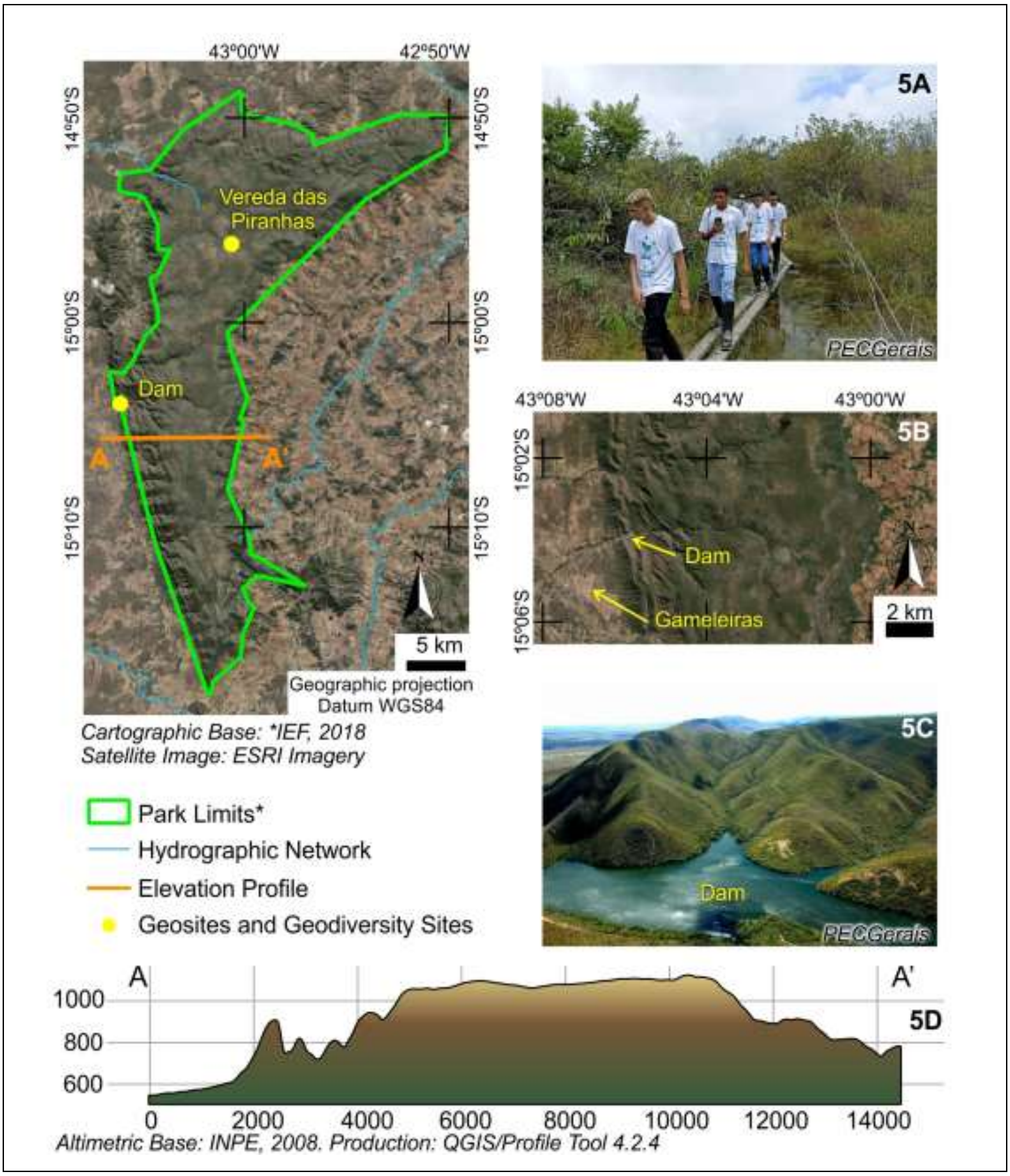
Caminho dos Gerais State Park – PecGerais

The park was created in 2007 (Figure 5) and had its Management Plan approved in 2021. It occupies an area of 56,237.3700 ha and is surrounded by the Caatinga biome (IEF, 2023a). Altitudes range from 462 to 1,103 meters, and it is home to 300 springs. Environmental education activities are frequent, but tourist activities await the Public Use Plan.

The rocks that occur in the park were strongly affected by Brasiliano Orogeny. Folds and subvertical layers may be identifiable even by satellite images (Figure 5B), especially in the western portion of the Park, characterizing a steep relief. Bersan et al. (2017) attribute these structures, which characterize a thin-skinned deformation style, to a strong control of basement blocks during orogeny. The thin sedimentary package is predominantly represented by rocks from the Espinhaço Supergroup and the Macaúbas Supergroup at its top. The set was subjected to compressive efforts and uplifted, through the reactivation of normal faults of basement rocks, which had originated during the Proterozoic extensional events. In the central and eastern portion of the park, in addition to the layers exhibiting a lower dip angle, geomorphological processes and the existence of a Cenozoic sedimentary cover led to the formation of an extensive plateau (Figure 5C).

The first site chosen, the Vereda das Piranhas Trail, is located in the plateau area (Figure 5A). It is a circular trail, with an extension of 1,450 m, which is already used in environmental education activities by the park's civil servants. The main point of interest along the route is a marshy field or remnant of a palm swamp (*vereda* in Portuguese) (IEF, 2023a), which may be dry depending on the time of year and the amount of precipitation during the previous rainy season. At a certain point in the trail, the substrate is composed of laterites. In addition to these, it is possible to observe an area heavily degraded by erosional processes due to the cultivation of eucalyptus that was carried out in the area. From an ecosystem services perspective, it is possible to discuss the relationship between the plateau and the supporting service of *providing a platform for human activities*, as it facilitates silviculture. Additionally, the regulating and provisioning services related to aquifer recharge areas and water sources can also be discussed (Table 4).

Figure 5. The limits of Caminho dos Gerais State Park, with the location of the selected points, are as follows: 5A – Environmental education activity conducted by IEF staff on the Vereda das Piranhas Trail. 5B – Enlarged section of Figure 5 showing in greater detail the folded and subvertical metasedimentary rocks due to compressive tectonic forces. 5C – Gameleiras Dam, whose construction was made possible due to the orientation and dip of the metasedimentary layers. 5D – Elevation profile A-A' showing the areas of the park with rugged terrain (west) and plateau areas (center and east)



Source: Authors, 2023.

At the Gameleiras Dam point (Figure 5C), the subvertical quartzite layers are very well exposed, allowing for the discussion of the tectonic events recorded in the region. From the point of view of ecosystem services, the geological structures favored the construction of the dam, characterizing a *supporting service of platform for human activities.*

Regarding the quantitative assessment methodology proposed by Brilha (2016), the two points are classified as geodiversity sites and have great educational potential. The Vereda das Piranhas point has low geotourism potential and medium risk of degradation. Its use, therefore, is more suitable for environmental education activities (Table 4).

Table 4. Abiotic, biotic and cultural aspects of interest and quantitative assessment of the geodiversity of the points of the Caminho dos Gerais State Park selected for educational and geotourism activities. SV – Scientific Value; EP – Educational Potential; TP – Tourist Potential; RD – Risk of Degradation

	Abiotic aspects	**Biotic Aspects**	**Cultural Aspects**	**Quantification**
Vereda das Piranhas Trail (713983 E / 8347805 S)	Aquifer recharge; Erosive processes; Laterites	Phytophysiognomies of Cerrado; Impacts of silviculture	Traditional Communities (Geraizeiros)	SV: 130 (Geodiversity Site) EP: 260 TP: 180 RD: 220
Gameleiras Dam (704105 E / 8333499 S)	Tectonic events (subvertical layers); Water resources	Phytophysiognomies of Cerrado	Leisure (downstream of reservoir)	SV: 180 (Geodiversity Site) EP: 260 TP: 180 RD: 195

Source: Authors, 2023.

Discussion

Geoconservation in protected areas

Mucivuna et al. (2022a), when examining research related to geoconservation in Brazilian national parks, found that despite many of them having their main attractions related to geological and geomorphological aspects, guidelines for the identification, assessment, and conservation of geodiversity are still in their early stages. These statements can also be extended to the state parks in Minas Gerais, with the caveat that some of them, created after 2007, are still in the process of developing their management plans.

Mucivuna et al. (2022b) emphasize that in national parks where geotourism and educational activities related to geodiversity are conducted, the selection of points was made through ad hoc consultations and partial inventories, which did not cover the entire park area. The authors claim that this may lead to misguided conservation efforts. Ideally, geoconservation strategies should be carried out after the complete inventory. Crofts et al. (2020) also argue that the inventory of the entire conservation unit should be the initial step for conservation strategies in protected areas.

The current scenario of the state parks studied in this work suggests the adoption of a distinct strategy. It is considered that initiatives can start from points and itineraries that are already used, or that are intended to be made available for public use. It is considered that in this way it will be possible to incorporate geodiversity more quickly into the public use activities of the parks. Thus, the inventory of the entire unit may represent the next step, which deserves to be discussed by the advisory councils, to be carried out in the medium or long term. The structuring of new attractions takes time, especially places whose main interests are related to geodiversity. It is understood that this structuring will be more easily implemented once the importance of geodiversity for the park is already recognized, both by managers and visitors.

In order to assist in the development of geoconservation initiatives in protected areas, a series of guiding principles were proposed by the International Union for Conservation of Nature – IUCN (Crofts et al., 2020). The discussion here strongly contemplates the items *"1 – The multiple values of geodiversity and geoheritage must be recognized"* and *"9 – The interaction and interdependence of geodiversity,* *biodiversity and cultural heritage must be recognized"*. Regarding item *"5 – Geoconservation strategies must include vulnerability and risk assessment"*, it is understood that studies must be carried out in conjunction with the other needs required for the implementation of the Public Use Plan. Several attractions already consolidated, for example, must be evaluated from a geotechnical point of view, such as the Talhado Canyon and Serrado Waterfall, both located in the PESNT.

Educational and geotourism potential

The effective incorporation of geodiversity into the public use actions of the state parks of MG, in addition to promoting the conservation of geopatrimony, will play an important social role in the search for sustainability. Environmental education activities aimed at elementary school students, as well as interpretative activities related to geotourism, will stimulate discussion about the goals related to the various Sustainable Development Goals – SDGs (UN, 2015). More specifically, the following SDGs can be mentioned: SDG 4 – Quality Education; SDG 6 – Drinking Water and Sanitation; SDG 12 – Responsible Consumption and Production; SDG 13 – Combating Climate Change; and SDG 15 – Terrestrial Life.

Regarding SDG 4 and SDG 15, geodiversity is relevant for contributing to the understanding of nature in an integrated way (Metzger et al., 2021; Odata et al., 2021), especially because geodiversity underpins biodiversity. The parks in question are essential for the goals of SDG 6 because they guarantee drinking water for the surrounding populations (Upton and McDonald, 2021).

Regarding SDG 12, it is understood that geotourism represents a way of encouraging sustainable tourism (Dowling, 2013). Indirectly, by stimulating the understanding of geological processes and the finitude of mineral resources, as they are not renewable, it is expected to encourage more rational use of natural resources (Mankelow et al. (2021). The PEM, in this sense, becomes especially relevant. The presence of infrastructure from a mining operation that has reached the end of its operational life serves as an example for this discussion (Mata-Perelló et al., 2018).

Understanding geological time, the changes that have occurred in the history of the Earth, and the impact of human activities on natural processes can contribute to the targets of Sustainable Development Goal 13 (Pereira et al., 2021). This is extremely pertinent to the northern region of Minas Gerais, in view of the projections of intensification of the semi-arid climate for the coming decades.

In addition to the SDGs, another interesting discussion linked to sustainability is the conflict between ecosystem services. In the case of PEM, from the site of the old mine, the drainage systems that feed the dam supplying the municipality, as well as the eucalyptus plantations in recharge areas, which pose a threat to water resources, are still visible. While on the one hand, the support service as a *platform for human activities* facilitates economic activities, on the other hand, it implies a threat to the provision service of *food and drink* (water resources). Without the park, silviculture activity could expand in the recharge areas, potentially compromising the supply of the municipality of Montezuma, due to the decrease in drainage flow.

In the case of PECGerais, before the creation of the park, the plateau areas were extensively occupied by silviculture and, to a lesser extent, also by livestock farming and agriculture. As a consequence, in addition to the decrease in the flow in the main streams, erosive processes were intensified by the removal of the primary vegetation cover (IEF, 2023a). The existence of Forest Ciliary Formations (Rodrigues, 2015) or remnants of *Veredas* (Borges et al., 2019) next to areas intensely affected by erosive processes in the old eucalyptus cultivation areas makes these places conducive to the discussion about the fragility of recharge environments and springs.

In the PESNT region, the plateau areas were mainly used for livestock farming. Considering that a significant portion of the plateaus is occupied by hydromorphic soils and Organosols (peatlands), the trampling of animals has led to soil compaction. The removal of primary vegetation cover also favored the development of erosion. These processes strongly impacted the drainage flow and was one of the main motivators for the creation of the park. Regarding abiotic ecosystem services, in addition to the impact on water resources, interference with carbon storage can also be mentioned, since there was degradation of peatlands, erosion, and the occurrence of fires.

Relationship between geodiversity, biodiversity and cultural aspects

The recognition of the intrinsic relationship between geodiversity and the occurrence of rare and endemic species is not new (Tukiainen et al., 2017). However, in addition to better understanding how this relationship occurs, it must also be effectively incorporated into interpretative activities in most protected areas. Regarding Espinhaço Range, the finding that its biological diversity is associated with elements of the physical environment was discussed by Gontijo (2010). The author also states that the geological and ecological importance of the Espinhaço Range, as a biome divider has already been mentioned since Eschwege's pioneering works in the 17th century.

In the north of Minas Gerais, there are transition areas between the Cerrado, Caatinga and remnants of the Atlantic Forest, creating ecotones and different phytophysiognomies. In the case of PESNT, the western boundary of the park represents the exact transition between the Cerrado and Caatinga biomes (Figure 3D). Geologically, this boundary coincides with the contact between the rocks of the Espinhaço Supergroup (Cerrado biome) and the Archean-Paleoproterozoic basement rocks of the Itacambira-Monte Azul Block, which have a flattened relief and lower elevations (Caatinga biome) (Figure 1A).

In PECGerais, Borges et al. (2019) and Rodrigues et al. (2015) identified the existence of various geoenvironments and phytophysiognomies of the Cerrado biome, resulting from the relationship between differences in terrain, soil, and vegetation. It is interesting to note that the park is surrounded by the Caatinga biome, where the flattened relief is composed of igneous and metamorphic rocks of the basement. Once again, there is an association between geodiversity and vegetation, where tectonic and lithological constraints resulted in different geomorphological and pedological conditions.

In the PEM in Montezuma, whose surroundings also correspond to the Cerrado biome, there is a direct relationship with the vegetation and the ways of life of traditional communities. For *Geraizeiros*, the collection of native species, such as *pequi*, is indispensable. The park is, in fact, located very close to the Nascentes Geraizeiras Extractive Reserve.

Another interaction of great relevance refers to the rupestrian grasslands, which occur in the highlands. There is a discussion about classifying them as OCBIL, which stands for Old Climatically Buffered, Infertile Landscapes. This term designates an ancient system that is climatically buffered and developed on infertile landscapes in terms of soil (Hopper, 2009; Silveira et al., 2016; Freire et al., 2021). According to Silveira et al., (2016) rupestrian grasslands are among the most biodiverse ecosystems in the world.

It is interesting to note the abiotic constraints related to the development of this ecosystem. The nutrient-poor and shallow soils stem essentially from the protolith, which correspond predominantly to quartzite in these parks. The climatic conditions in part refer to the uplift and the resistance to weathering of these rocks. Rupestrian grasslands develop at altitudes above 900 meters. These factors propitiated, or at least contributed to, the endemism observed in the rupestrian grasslands. And these species remain protected, in part also due to the rugged relief of the edges of the highlands, which makes access difficult and minimizes the impact of human actions.

While the IUCN recommends that nature management be carried out in an integrated manner, incorporating both biodiversity and geodiversity, with respect to environmental interpretation, several studies emphasize the need to also include the relationship with the cultural aspects of the territory. Dowling (2011) refers to this approach as the ABC Concept, which includes abiotic (geodiversity), biotic (biodiversity), and cultural aspects. This approach is interesting precisely because it presents an integrated view of nature, with its various constituents. According to the author, this tends to arouse greater interest from visitors.

Pásková et al. (2021) point out that the great challenge is, in fact, to be able to reconcile the three aspects during the interpretative activity. It is not trivial to make the public understand the interconnections between the three aspects, meaning that the ABC Concept is effectively incorporated and practiced in interpretative activities related to geodiversity. To make it easier to achieve the objectives, the ideal is to apply the ABC Concept from the beginning of the development of the interpretative content. According to the authors, experience shows that it is much more difficult to adapt preexisting content that was developed from a fragmented perspective of nature than to develop interpretive content and products that, from the outset, follow the ABC Concept.

Local and regional development

In addition to educational aspects, parks can also contribute economically to the surrounding municipalities through geotourism. The PEM stands out from the others in this regard, as it has the facilities of an old amethyst mine inside. The tourist use of former mining areas has been increasingly used as a way to promote local economic development (Prosser, 2019). These activities should be designed to strengthen the “sense of belonging” in relation to the place, as well as the “mining” and ecological identity of the landscape (Mata-Perelló et al., 2018). In this way, it is possible to increase the attractiveness of the territory from a tourism perspective.

Montezuma is already one of the main tourist destinations in the region, where the municipality's main attraction is also related to geodiversity, due to the occurrence of hot springs. The potential expansion of tourism offerings to other locations where the attraction is also related to the abiotic aspects of nature allows us to conclude that geodiversity can be the primary driver of this “sense of belonging.”

Tourist use would also be important to help conserve the site's mining heritage. The mine operated from 1936 to 2007. However, despite being located within the park, the structures that remain on the site have been subject to vandalism, including the removal of part of the machinery (Figure 4D) and piles of waste. There are currently not enough civil servants to control access to the site of the former mine. Tourist use, with the proper implementation of infrastructure and surveillance, would contribute to inhibiting vandalism.

Final Remarks

Considering that various aspects related to the United Nations Sustainable Development Goals have also been identified in the selected geosites and geodiversity sites, it can be concluded that environmental interpretation activities will contribute to sustainability. This awareness is extremely relevant, especially because projections indicate an increase in water scarcity in northern Minas Gerais in the coming decades. Interpretive activities should also encourage the public to perceive that conservation initiatives are not limited to state parks. Visitors should understand that the existing protected areas are not sufficient to mitigate the effects of climate change in the region, and there is a need to expand the areas of conserved nature.

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