







Potential Ecosystem Services Contribution of Geodiversity in Carajás National Forest, Amazon Biome, Pará, Brazil

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Abstract

In the 1970s, growing environmental concerns led researchers to address ecological issues from an economic perspective, highlighting society's dependence on ecosystems. This resulted in the emergence of the terms natural capital and ecosystem services, which are defined as the benefits people obtain from ecosystems. The traditional approach to ecosystem services overlooks the services provided by geodiversity, which comprises the diversity of non-living nature. This article aims to quantitatively assess and map the ecosystem services provided by geodiversity in the Carajás National Forest, located in Pará, Brazil, referencing its management plan. The study area also includes the Campos Ferruginosos National Park. The methodology was in two main stages: (i) Identification and classification of ecosystem services provided by geodiversity; (ii) Counting occurrences of each type of geodiversity service. Variables were grouped into regulation, support, provisioning, and cultural categories. Considering the relevance of cave occurrences, speleostystemic services were included. Ecosystem services in the Carajás National Forest mining zone are very high in all categories, mainly from the presence of over 900 caves. This area includes iron, manganese, deactivated gold, licensed but not yet installed copper, sand, and granite mines. The mining zone aims to minimize the impact on adjacent areas and prioritize recovering degraded areas with native species, prohibiting invasive exotics. The management plan does not directly address caves crucial for ecosystem regulation, water quality, and soil stability. Besides caves, high-altitude lakes play a fundamental role in regulating the hydrological cycle and promoting water quality. Provisioning services are very high in the mining zone but only medium in the Sustainable Forest Management zone, where timber management is unfeasible due to mining impacts. The Preservation Zone, classified as having low potential for geodiversity ecosystem services, maintains nature in its most primitive state. It is essential for regenerating other zones and preserving ecosystems and genetic resources.

Keywords: Amazon caves, Ecosystem services, Geodiversity, Management plan, Environmental management

Introduction

The survival and well-being of humanity are intrinsically linked to its relationship with nature. Diamond (2005) provides historical examples of how ancient and contemporary societies choose failure or success based on their interactions with the planet and their use of natural resources. By

exploring cases such as the Mayans, the Vikings, and Polynesian societies, Diamond (2005) identified recurring patterns in environmental decisions and natural resource management as crucial elements leading to the decline of societies from the loss of ecosystem services, including habitat loss, soil retention, biomass production, and water reg-

ulation.

Growing environmental concerns during the 1970s and 1980s led researchers to approach ecological issues from an economic perspective, highlighting society's profound dependence on ecosystems. This stimulated public interest in biodiversity conservation (Gomez-Baggethun *et al.* 2010). During this period, environmental studies were significantly revised to incorporate environmental externalities into cost-benefit analyses and increased awareness of human influence on the natural world (Gomez-Baggethun *et al.* 2010; Cooke 2022). From this historical context, in the late 20th century, the terms *natural capital* and *ecosystem services* emerged. Natural capital was defined by Costanza and Folke (1997) as identifiable and physical capital (e.g., trees, minerals, water, etc.) responsible for delivering *ecosystem services*, referring to the benefits people obtain from ecosystems (Reid *et al.* 2005; Cooke 2022). Ecosystem services, as defined by Costanza and Folke (1997), encompass: (1) gas regulation, (2) climate regulation, (3) disturbance regulation, (4) water regulation, (5) water supply, (6) erosion control, (7) soil formation, (8) nutrient cycling control, (9) waste treatment and detoxification, (10) pollination, (11) biological control, (12) habitat and refuge, (13) food production, (14) raw materials for primary production, (15) genetic resources, (16) recreation, and (17) cultural.

The modern conception of ecosystem services comprises a multifaceted body of knowledge from realizing natural resource constraints (Marsh 1864) and the study of ecosystems (Lindeman 1942). It encompasses diverse perspectives, ranging from Aldo Leopold's land ethic to the exploration of experimental ecology and the role of biodiversity in ecosystem dynamics (Mooney and Ehrlich 1997; Fisher *et al.* 2009; Patterson and Coelho 2009). This concept has evolved into a comprehensive framework for understanding and articulating the

intricate interplay between human well-being and ecosystem vitality, providing essential foundations for sustainable natural resource management (Cooke 2022).

The understanding of the benefits provided by nature to people, as expressed in the concept and framework of ecosystem services, has given rise to various approaches that are increasingly being applied to support the sustainable management of biodiversity and ecosystems (Ingram *et al.* 2012). A recurring challenge in the literature on ecosystem services, particularly related to their categorization, lies in the diversity of methods used to assign economic value to them. This has resulted in a lack of cohesion in the initial literature on the subject (Cooke 2022). The Millennium Ecosystem Assessment (MEA) provided clarity by presenting a comprehensive framework that categorizes ecosystem services into four groups: provisioning, regulating, cultural, and supporting services (MEA 2005). Since 2016, the Common International Classification of Ecosystem Services (CICES) initiative has reduced the categories to three: provisioning, regulating, and cultural services, considering supporting services as ecosystem functions rather than a specific category (CICES 2021).

However, traditional approaches overlook the services provided by geodiversity. This issue has been the subject of continuous debate among geoscientists, as this exclusion may compromise a comprehensive assessment of natural environments (Gray 2018; Fox *et al.* 2020; Alahuhta *et al.* 2022). The emphasis on biological ecosystem services is concerning, considering that an ecosystem is defined as a complex and dynamic assemblage of plant, animal, and microbial communities and their non-living environment interacting as a functional unit (de Groot *et al.* 2002; Worm *et al.* 2006; Luck *et al.* 2009; Raudsepp-Hearne *et al.* 2010).

Geodiversity, the diversity of non-living nature,

comprises sets, structures, and systems of geological, geomorphological, soil, and hydrological components, as well as their contributions to landscapes, and the services they provide either in isolation or through interactions with biotic nature. Geodiversity actively contributes to a wide variety of ecosystem services across all categories. It plays both direct and indirect roles in the delivery and maintenance of these services (Gordon and Barron 2013; Prosser 2013). Ecosystem services derived from geodiversity are described as functions offered by elements of geodiversity, either directly or indirectly, for the benefit of society and future generations (Gray 2013).

Considering the MEA general approach, which directly excludes abiotic elements from the classification of ecosystem services, Gray's (2019) analysis focuses on services directly linked to geodiversity. This approach considers the traditional categories of regulating, supporting, provisioning, and cultural services and encompasses *knowledge services*: geodiversity, especially geological aspects, plays a crucial role in understanding Earth's evolution and life forms. The primary focus of the ecosystem services approach related to geodiversity, therefore, lies in finding a comprehensive way to manage the natural environment sustainably, considering land management, water management, and living organisms, reflecting societal aspirations and climate change concerns (Gordon et al. 2012; Hjort et al. 2015; Garcia 2019). Geodiversity is an emerging topic with unexplored potential to ensure ecosystem functionality and good living conditions for people amidst environmental changes (Alahuhta et al. 2022). The quantification of geodiversity-derived ecosystem services is a rare practice, and the available quantitative assessments are still uncommon, utilizing adaptations of various methodologies (Reverte et al. 2020, Schlattmann et al. 2022, Santos et al. 2023, Cusens et al. 2023, Scammacca et al. 2024).

In this context, the primary aim of the article is to conduct a quantitative assessment and map the potential ecosystem services provided by geodiversity in the Carajás National Forest, located in the state of Pará, Brazil. Designated as a sustainable use Conservation Unit (UC) under the National System of Conservation Units (SNUC) (Brazil 2000), the study seeks to integrate this type of analysis into the management framework of the Conservation Unit. Notably, the study area also encompasses the Campos Ferruginosos National Park, which shares a portion of its territory with the Carajás National Forest.

The study area was chosen for its ecological and geological uniqueness, particularly its unique ferruginous geosystem and the coexistence of mining with conservation zones. This combination makes the region crucial for understanding and applying geodiversity and ecosystem services concepts, providing a model for conservation strategies that can be replicated in similar areas.

Study Area

Carajás National Forest is located approximately 540 km south of Belém, the capital of the state of Pará, in the southeastern Brazilian Amazon. With an area of 411,948 hectares, it encompasses the municipalities of Parauapebas, Canaã dos Carajás, and Água Azul do Norte (Fig. 1).

Over the years, this region has undergone significant transformations, especially since the late 1950s, especially through the construction of the Belém-Brasília highway, the implementation of the I and II National Development Plans, the construction of the Trans-Amazonian Highway, and the implementation of tax incentive policies.

Mineral extraction has been crucial too. In 1967, United States Steel discovered iron mineral reserves in Carajás, and in 1974, Amazônia Mineração S/A obtained the right to exploit these resources. In 1980, the Brazilian government

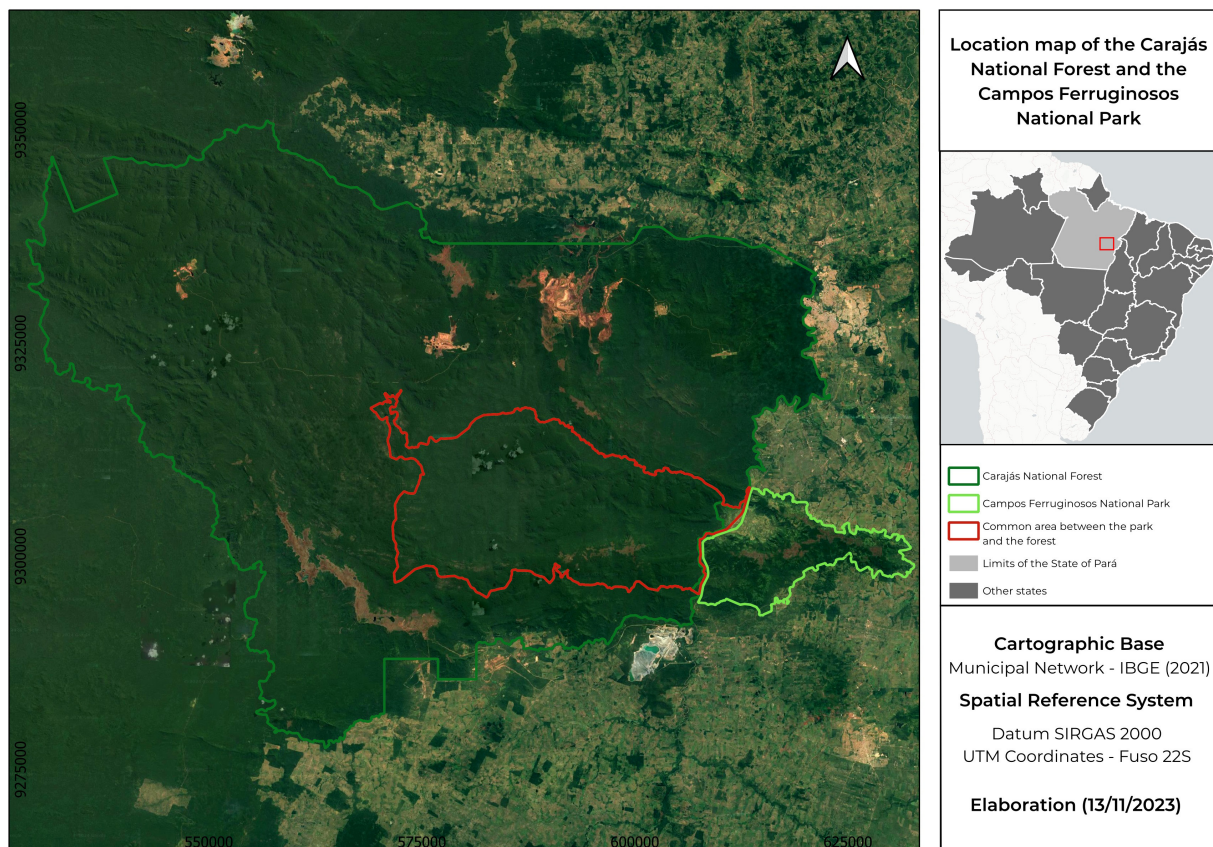


Figure 1. Location map of the study area. Prepared by the authors.

launched the Great Carajás Program to coordinate the development of Eastern Amazonia, offering benefits to enterprises in the area. The Carajás Iron Project began in 1981, with Companhia Vale do Rio Doce (CVRD) assuming control of Amazônia Mineração S/A. With the privatization of CVRD, now VALE, the Brazilian government created a sustainable conservation unit called Carajás National Forest in the same area, allowing mining activities to continue. This conservation unit is managed by the Chico Mendes Institute for Biodiversity Conservation (ICMBio), a Brazilian agency responsible for federal conservation units, and for the protection and conservation of biodiversity.

In the category of Sustainable Use Conservation Units, alongside significant Indigenous Lands, the creation of the Carajás National Forest aimed to reconcile nature conservation with the sustainable use of a portion of natural resources. The National Forest is located within one of the world's most im-

portant geosystems, the Carajás Ferruginous Geosystem. Ferruginous Geosystems are geographical areas primarily composed of iron-rich rock types with complex landscapes and remarkable geodiversity, including caves (Ruchkys 2015).

The region is drained by the Itacaiúnas river basin, which flows into the Araguaia-Tocantins fluvial-hydrological system and is characterized by a series of discontinuous mountain ranges and extensive valleys. The main elevations, known as the Northern Range and Southern Range, are part of the so-called Carajás Fold, where high-grade iron ore bodies (> 64% Fe) are located within jaspilite layers (Lobato 2005).

Method

The methodological procedures for quantifying and spatializing geodiversity ecosystem services were adapted from Santos et al. (2023) and consist of two main stages: (i) identification and classi-

fication of ecosystem services (ES) provided by geodiversity; (ii) counting occurrences of each type of geodiversity service. These procedures are detailed below.

Based on the availability of data for the research area, the geodiversity service variables were grouped according to Gray's (2019) proposal into the following categories: regulatory, supporting, provisioning, and cultural (including knowledge services) (Table 1). Considering the relevance of the area in terms of the occurrence of caves,

some services proposed by Urban *et al.* (2022) and Menin and Bacci (2023) were included; the latter authors specifically refer to these services as spelecosystemic services.

In addition to data availability, the selection of variables for mapping geodiversity ecosystem services considered their relevance across various ecosystem service categories, such as regulation, support, provision, and cultural services. Caves were included for their role in regulating external ecosystems and providing habitats, while

Table 1. Geodiversity services considered, based on Gray (2019), Urban *et al.* (2022), Menin and Bacci (2023).

Service	Category	Considered variable
Regulation	Regulation of external ecosystems	Caves
	Regulation of water quality	Lakes Wells
	Soil processes (weathering; soil profile development) and soil as a growth medium.	Soils
	Habitat provision (habitats, caves, limestone pavements, outcrops, cliffs, escarpments, and salt flats)	Caves
Support	Land and water as platforms for human activity	Lithology Aerodrome Pipelines Highways Railways
		Lakes
		Active Mining and Metallurgical Venture
Provision	Burial and storage (human and animal burials, municipal landfills, radioactive waste storage, carbon capture and storage, water stored in aquifers, reservoirs, and lakes).	Lakes
	Industrial minerals (fertilizers, pharmaceuticals, metals, alloys)	Projected Mining and Metallurgical Venture
	Industrial minerals (fertilizers, pharmaceuticals, metals, alloys)	Mineral Resources
	Industrial minerals (fertilizers, pharmaceuticals, metals, alloys)	Mining Titles
Cultural	Shelter provision	Caves Tourism
	Environmental quality (local landscape characteristics; therapeutic landscapes, landscapes for health and well-being)	Lakes Caves
	Cultural, spiritual, and historical (folklore; sacred sites; historic stone buildings; sense of place).	Archaeological Sites
	Artistic inspiration (geological materials in sculptures; inspiration for art, literature, music, poetry)	Geomorphology
	History of scientific research (early on, identification of discrepancies, fossils, rocks)	Lithology

lakes and wells were selected for their importance in water quality regulation and storage. Lithology and geomorphology were deemed crucial for understanding geological processes and the availability of mineral resources, with soils playing a fundamental role in agriculture and water regulation. Additionally, variables such as aerodromes, pipelines, highways, and railways were included for their significance to infrastructure and the sustainable use of resources, reflecting the role of land and water as platforms for human activity. The analysis of active and planned mining ventures, along with the availability of mineral resources and mining titles, enabled the assessment of impacts and opportunities related to mineral extraction. Archaeological sites, lakes, and caves were also incorporated for their cultural, ecological, and landscape value. Together, these variables provide a comprehensive and integrated view of geodiversity ecosystem services, supporting the analysis necessary for sustainable territorial planning and management.

The mapping of geodiversity services is used as a reference for the different zones of the National Forest management plan (ICMBio 2016). In Brazil, the management plan of the Conservation Unit is a technical document that, based on the objectives defined at the time of its creation, establishes zoning and rules that guide its use (Brazil 2000). To meet the general objectives of the National Forests and the specific objectives of the Carajás

National Forest (Carajás National Forest), seven zones were defined, namely: Preservation, Primitive, Public Use, Special Use, Sustainable Forest Management, Mining, and Conflictive (ICMBio 2016) (Table 2).

It is important to emphasize that the Campos Ferruginosos National Park encompasses a region not included within the boundaries of the Carajás National Forest, thereby lying outside the scope of the latter's management plan. An adaptation was implemented in response to this situation, considering the intersecting area between the two units, designated as a preservation zone. This measure was extended to encompass the portion not covered by the Carajás National Forest.

The mapping of geodiversity services potential in this manner aims to consider space in functional areas according to their characteristics and quantities of services present. These functional spaces can be based on management plan zoning (as in the case of this article), watersheds, municipal boundaries, and in short, different types of areas for planning and management.

After selecting the variables representing the different types of geodiversity services, cartographic data were reprojected to the geodetic coordinate system - Geocentric Reference System for the Americas (SIRGAS) 2000 (SIRGAS 2000). A table was constructed for each zone, relating the number of occurrences of each geodiversity ser-

Table 2. Zones established in the Management Plan of the Carajás National Forest incorporating the Campos Ferruginosos National Park. Source: (ICMBio 2016).

Zone	Area (ha)	% of Carajás National Forest
Preservation	59,696.63	15.13
Primitive	57,623.97	14.06
Public Use	7,582.05	1.92
Special Use	16,237.38	4.11
Sustainable Forest Management	196,551.88	49.81
Mining	55,486.63	14.06
Conflictive	1,431.82	0.36

vice to the area of the zone.

Most of the data was obtained through the National Spatial Data Infrastructure (INDE) portal, a Brazilian government platform that facilitates access to, integration of, and management of geospatial data, providing a comprehensive and integrated view of the national territory: Geomorphology, Soils (Brazilian Agricultural Research Corporation-Embrapa); Wells (National Water Resources Information System-SNIRH); Aerodromes and Railways (National Civil Aviation Agency-ANAC); Highways and Railways (National Department of Transport Infrastructure-DNIT); Active Mining and Metallurgical Ventures, Projected Mining and Metallurgical Ventures, Mining Titles: ANM (National Mining Agency); Pipelines (Brazilian Institute of Geography and Statistics-IBGE); Archaeological Sites (National Institute of Historic and Artistic Heritage-IPHAN).

The remaining data were obtained from the following sources: Caves (National Center for Cave Research and Conservation-CECAV); Lithology, Mineral Resources, and Geotourism (Geological Survey of Brazil-SGB-CPRM); Geotourism, Ecotourism (websites of the municipalities within the study area).

The next step involved counting the occurrences of each type of geodiversity service per category, considering the Management Plan zones (Table 3). The counting was carried out for each of the zones defined in the Management Plan of the Carajás National Forest (Flona Carajás), identifying and recording the number of occurrences of each variable within these zones. This process involved a detailed analysis of how many times each specific variable, such as caves, archaeological sites, or soil types, appears in each zoning zone. Each occurrence was recorded in a way that reflects the spatial distribution of these elements in the different management areas of Flona. This approach allowed for a more accurate understanding

of the presence and concentration of the variables in different zones, facilitating the spatialization of the data and the subsequent analysis of the distribution of ecosystem services associated with geodiversity in the region.

Results

The potential of services considering all categories is very high, exclusively in the mining management zone (Fig. 2). This behavior is equally repeated for cultural, regulation, and support services. This classification is mainly influenced by caves, with more than 900 occurrences registered in this area, surpassing the number of other zones.

The mining zone (Fig. 3) is defined in the management plan as the areas corresponding to the rights of exploration and mining of mineral deposits and as the associated infrastructure duly registered with the National Mining Agency (ANM). This area encompasses existing iron and manganese mines, a deactivated gold mine, licensed but not yet installed copper mines, and sand and granite mines used internally by the mining company. In the same zone, iron ore deposits are not yet licensed (ICMBio 2016).

The objective of the mining zone (ICMBio 2016) is to concentrate mining activities, aiming to minimize the impact on adjacent areas and other zones. Guidelines are established, such as ensuring the recovery of degraded areas, prohibiting deforestation for forming of waste rock piles and prioritizing using exhausted pits for waste rock deposition or disposal outside the National Forest. Additionally, priority is given to the use of native plant species in the recovery of degraded areas, with the strictly prohibited use of invasive exotic species. Furthermore, areas containing endemic species of the Carajás National Forest may only be mined if the species is preserved in other protected areas, ensuring the maintenance of viable populations.

It is important to note that the Management Plan

Table 3. Number of occurrences of the variables considered by zone of the Management Plan. Source: (ICMBio 2016).

Variable	Service Category	Forest Management	Mining	Preservation	Primitive	Conflictive Use	Special Use	Public Use
Caves	Regulation Support Provision Cultural	292	946	257	55	0	49	0
Archaeological Sites	Cultural	17	68	1	0	0	5	0
Lakes	Regulation Support Cultural	7	7	0	0	0	5	0
Lithology	Support Cultural	12	8	5	7	2	9	2
Geomorphology	Cultural	7	5	4	7	3	6	2
Soils	Support	9	6	6	6	4	6	3
Geotourism, ecotourism	Cultural	1	4	1	0	1	2	1
Wells	Regulation	0	82	7	0	0	1	0
Aerodrome	Support	0	1	0	0	0	1	0
Pipelines	Support	0	0	1	0	0	0	0
Highways	Support	0	1	0	1	0	1	0
Railways	Support	0	0	0	0	0	1	0
Active Mining and Metallurgical Venture	Provision	0	4	1	2	0	0	0
Projected Mining and Metallurgical Venture	Provision	2	2	4	1	0	2	0
Mineral Resources	Provision	14	11	9	8	0	3	1
Mining Titles	Provision	123	44	33	50	9	67	13

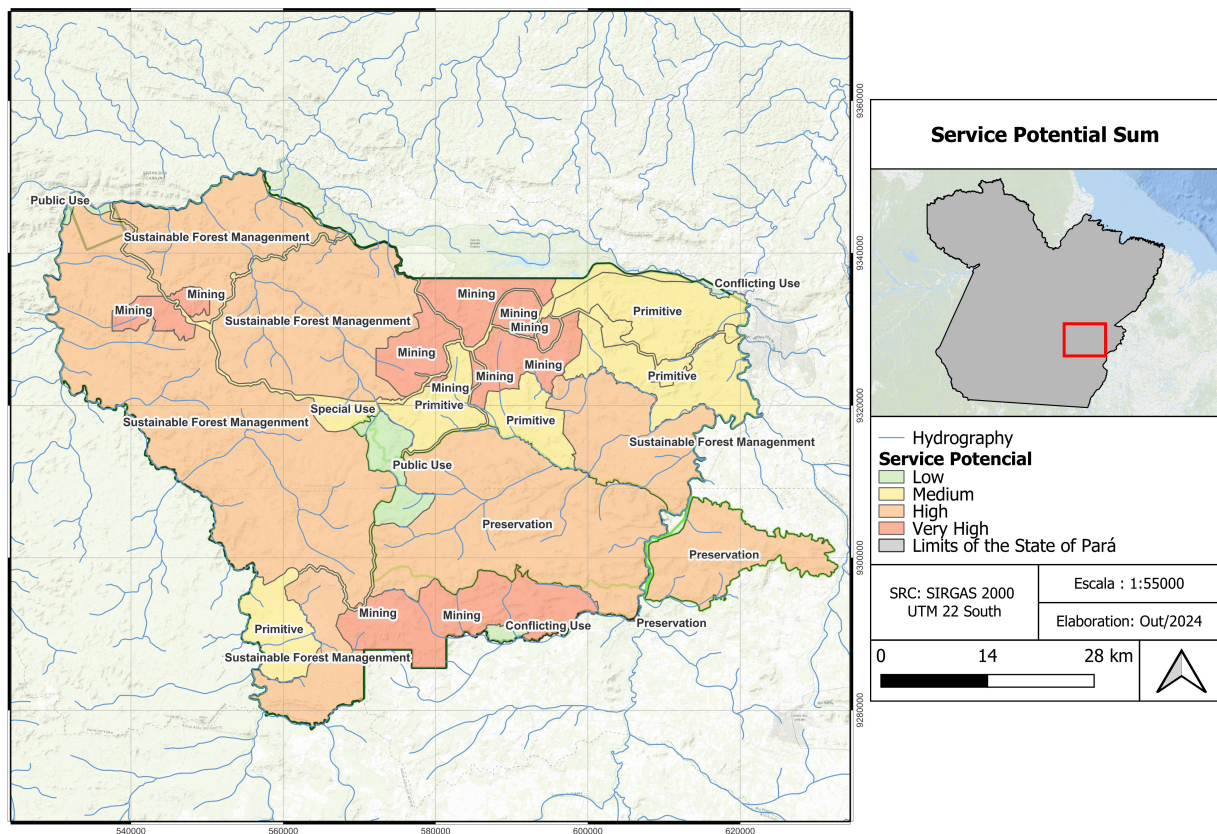


Figure 2. Synthesis map of geodiversity ecosystem services potential in the Carajás National Forest. Developed by the authors.



Figure 3. One of the iron ore mines located in the mining zone of the Carajás National Forest.

does not cover aspects related to caves, focus solely on legal matters, and does not provide guidelines for mining activities concerning this aspect. Caves are crucial for regulating ecosystems, impacting the quality and stability of surrounding environments, especially in ferruginous geosystems. Therefore, it is crucial to consider aspects such as the conservation of underground biodiversity,

water quality maintenance, soil stability, and other ecosystem regulation services provided by this unique environment. Additionally, iron caves play a significant role in scientific, archaeological, educational, and touristic contexts within the realm of cultural ecosystem services (Fig. 4).

Regarding supporting ecosystem services, caves



Figure 4. Examples of landscapes. **A)** Signpost for the Gruta Trail, **B)** Fieldwork at the Gruta do Mapiquari, used by the ICMBio team for educational activities, and **C)** Archaeological excavation in one of the caves analyzed.



Figure 5. Panoramic view of Lagoa do Violão, one of the high-altitude lakes of the Carajás Ferruginous Geosystem that stands out in the landscape. Photo by Darcy dos Santos.

play a crucial role in maintaining underground biodiversity. They provide unique habitats for many organisms adapted to conditions of darkness, low food availability, and extreme temperature variations. These cave ecosystems, often delicately balanced, play a crucial role in conserving endemic species and promoting genetic diversity.

Beyond caves, the variable lakes also significantly influence the classification of very high potential for cultural, regulation, and support services in the mining zone. In this zone, high-altitude lakes play a crucial role in regulating the hydrological cycle (Fig. 5).

Functioning as natural reservoirs, these ecosystems store water during surplus periods, strategically releasing it during scarcity phases. This process plays a fundamental role in maintaining a stable water flow. Additionally, lakes are prominent in promoting water quality, serving as efficient natural filters that remove pollutants and sediments. Furthermore, their crucial role in the regional hydrological cycle for aquifer recharge can be highlighted. Regarding cultural value, high-altitude lakes stand out as unique geographic features, endowed with remarkable scenic beauty. Located in mountainous areas, they play a crucial role in shaping landscapes, serving as prominent elements in the cultural identity of the regions where they are located. Additionally, their presence can significantly catalyze tourism and recreation, providing visitors with unique experiences and generating economic opportunities for local communities.

The provisioning ecosystem services demonstrated a different behavior than other services in the studied region. These services remained classified as very high in the mining zone, while in the Sustainable Forest Management zone, they were at a medium level. The latter covers the largest area of the Carajás National Forest (CNF) because of its potential for multiple uses, identified through

the exploration of non-timber products, such as jaborandi, and the viability of mineral research. Although timber forest management is among the objectives of the CNF, the ICMBio considers it unfeasible to reconcile mining with timber exploitation in this conservation unit due to the complex arrangements and the impacts of current mining activities. Some areas of metallophilous savanna were included in the Sustainable Forest Management zone to ensure the continuity of environmental and geological research. These studies aim to support a forthcoming review of the management plan, enabling the inclusion of these areas in appropriate zones for mining or conservation, according to the results of the studies conducted (ICMBio 2016).

It is worth noting that the Preservation Zone in the Management Plan was classified, in this study, as having a low potential for geodiversity ecosystem services. The low density of caves, when compared to occurrences in the mining area and the absence of lakes, contributed to this classification. The Preservation Zone is where nature remains in its most primitive state, preserved free from any human interventions, representing the highest level of preservation. It is a fundamental matrix for regenerating other zones where regulated human activities are permitted. This zone protects ecosystems, genetic resources, and environmental monitoring. From a scientific standpoint, it is important to highlight that the Preservation Zone may also have significant potential regarding speleological heritage and geodiversity besides preserving ecosystems and genetic resources. It is highly suitable to allocate resources for exploring this area to conduct a detailed mapping of the ecosystem services that the present geodiversity can provide. This would include the identification and conservation of caves and unique geological formations and the understanding of geodynamic processes and associated ecosystem services, such as hydrological regulation, maintenance of soil quality, and

conservation of underground biodiversity. This information will be valuable for supporting more effective management and conservation measures, aiming to ensure the integrity and resilience of these natural systems.

Final Remarks

Recognizing the importance of replicability and accessibility of the adopted methodology, it is crucial to emphasize that the approach used in this study is simple and easily replicable. Adapting the methodological procedures proposed by Santos et al. (2023), the aim was to ensure an accessible and efficient methodology for the preliminary assessment of ecosystem services provided by geodiversity in the Carajás National Forest.

It is important to clarify that, although the methodology used in this study is based on relatively simple procedures, such as the counting and spatialization of variables using GIS tools, it requires careful application to ensure the accuracy of the results. The simplicity of the approach lies in its overall structure, which can be applied to other regions. However, its replicability depends not only on the availability and quality of data but also on a proper understanding of geodiversity concepts and the ability to accurately interpret the geospatial variables involved.

When using the method of counting elements within an area in vector format, certain advantages stand out, such as the flexibility to manipulate and visualize different types of features (points, lines, and polygons), making it particularly suitable for comparing different zones within a conservation unit, for example. However, this format may not efficiently capture continuous variations or gradients within the studied area, which are better represented and analyzed in raster data, such as in studies of land cover or topographical variations.

The results reveal that the mining management zone emerges as a standout area, showing signifi-

cantly high potential for various ecosystem services, including cultural, regulatory, and support services. This prominence is directly related to the significant presence of caves and high-altitude lakes, which play crucial roles in regulating local ecosystems.

However, it is important to acknowledge that the results obtained should be interpreted cautiously because of some limitations. Firstly, data availability may vary among different zones of the Conservation Unit, which could affect the accuracy and comprehensiveness of the analyses conducted. Additionally, it is important to consider the potential discrepancy among systematic studies conducted in the region, partly due to differences in sampling effort intensity and accessibility, especially regarding speleological heritage surveys. Lakes, in turn, are likely underrepresented due to restrictions imposed by definitions regarding their presence and dimensions in different seasons and due to annual variations in rainfall and surface moisture retention.

These limitations highlight the need for future research and more detailed assessments that can complement and improve upon the results presented in this study. Once patterns or areas of interest have been identified through an initial analysis using the vector method, the raster method can be employed to investigate in greater depth the continuous variations or gradients within these areas, such as changes in land cover, vegetation density, or elevation. This combination of approaches allows for a more robust and comprehensive analysis, where the vector method provides a clear and detailed view of discrete features, while the raster method deepens the understanding of more complex and continuous spatial phenomena. Therefore, this sequence can be highly effective in studies of geoconservation, territorial planning, and environmental monitoring.

Nonetheless, even with these considerations, the results offer valuable insights into the potential

of geodiversity ecosystem services in the region. They can serve as a solid foundation for guiding the management and conservation of the Carajás National Forest and the Campos Ferruginous National Park. They could contribute to developing more effective and sustainable management strategies for these important conservation units.

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Conflict of interest statement

The authors declare that there are no conflicts of interest associated with this study.

Authors' Contributions

Úrsula de Azevedo Ruchkys led the writing of the manuscript, with significant contributions from Paulo de Tarso Amorim Castro and Heros Augusto Santos Lobo. Paulo Henrique Maciel Pádua was responsible for the figures and data systematization under the guidance of Úrsula Ruchkys de Azevedo, Paulo de Tarso Amorim Castro, and Heros Augusto Lobo. All authors critically reviewed the work, approved the final version, and agreed to be accountable for all aspects of the work.

Availability of data and materials

The data that support the findings of this study are available from the corresponding author, upon reasonable request

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