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Speleosystemic Services: how to characterize caves from the perspective of Ecological Economics and Geosystemic Services?

Serviços Espeleossistêmicos: como caracterizar as cavernas sobre o ponto de vista da Economia Ecológica e dos Serviços Geossistêmicos?

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ABSTRACT

The direct and indirect benefits that ecosystem services provide to human beings can be of countless natures: from the water we use for various purposes, to the biodiversity, resources, and minerals that have sustained the evolutionary history of civilizations. Faced with the recent threats that the Brazilian speleological heritage has been suffering, this article aims to contribute to the discussion on the benefits that caves have in this context, from shelter to the first civilizations to the source of information about the climatic past, and advanced industrial drug research in the future. As an analysis resource, the present study applies the concepts of ecosystem services to the karst environment and applies a method of surveying "spelesystemic" services with the Devil's Cave (Gruta da Tapagem). As a basis for contextualization, and to historically place the reader on the topic, the text reviews how discussions related to ecosystem services emerged and evolved in recent decades. Thus, the objective is to present arguments based on Ecological Economics to support conservation strategies for karst regions, as well as information that contribute to better scientific dissemination and environmental education actions. It is believed that categorizing the benefits that caves have on human populations can be a useful argumentation resource in response to the lack of knowledge of the speleological heritage in the face of the threats it has been suffering.

Keywords: Ecological economics; Ecosystem services; Caves; Geoconservation.

RESUMO

Os benefícios diretos e indiretos que os serviços ecossistêmicos promovidos pela natureza prestam ao ser humano podem ser de inúmeras ordens: desde a água que é utilizada para diversos fins, até a biodiversidade, os recursos e os minérios que sustentaram a história evolutiva das civilizações. Diante das recentes ameaças que o patrimônio espeleológico brasileiro vem enfrentando, como tentativas de alteração dos decretos que regem sua proteção, este artigo busca contribuir para a discussão sobre os benefícios que as cavernas proporcionam nesse contexto, desde abrigo às primeiras civilizações até fonte de informações sobre o passado climático e pesquisas farmacoindustriais avançadas no futuro. Como método de análise, o presente estudo aplica os conceitos de serviços ecossistêmicos ao ambiente cárstico, assim como um método de levantamento de serviços "espeleossistêmicos" para a Caverna do Diabo (Gruta da Tapagem). Para contextualizar, o texto revisa como as discussões relacionadas aos serviços ecossistêmicos emergiram e evoluíram nas últimas décadas. O objetivo é, portanto, apresentar argumentos embasados na Economia Ecológica para sustentar estratégias de conservação em regiões cársticas, além de fornecer informações que contribuam para uma divulgação científica mais eficaz e para ações de educação ambiental. Acredita-se que categorizar os benefícios que as cavernas oferecem às populações humanas possa ser um recurso útil para argumentar contra o desconhecimento do patrimônio espeleológico diante das ameaças que enfrenta.

Palavras-chave: Economia ecológica; Serviços ecossistêmicos; Cavernas; Geoconservação.

INTRODUCTION

It was not uncommon, a few decades ago, for human beings to represent nature as a hostile environment, a barrier to be overcome in the search for progress and economic growth (Bueno, 2008; McDonough and Braungart, 2010). During industrial expansion, the environment was not understood as a set of integrated and finite ecosystems, but as an inexhaustible source of resources and a depository, with an infinite capacity for renewal and absorption of pollutants (McDonough and Braungart, 2010; Monteiro and Mariani, 2012).

The Industrial Revolution, in the second half of the 18th century, in addition to the long-awaited progress, also brought environmental disasters and economic crises unprecedented in human history (Carson, 2015; Pott and Estrela, 2017). Events that took place between the 1950s and 1970s, such as Smog in London, Silent Spring in the USA, and Minamata Bay in Japan, were responsible for thousands of deaths, also contributing to the beginning of a broader understanding of the relationships between human beings and the natural environment. From the 1970s onwards, governments, media, and society began to highlight the threats of continuous human predatory action on ecosystems at the expense of economic growth (Kakazian, 2005).

It is noteworthy that the concept of ecosystem services used in this study is based on Ecological Economics, which has as its elementary premise the establishment of maximum limits of degradation and minimum limits of conservation of natural capital, to delimit the universe of possibilities for the appropriation of ecosystems by the economic subsystem (Igari et al., 2020). Ecological Economics, in opposition to the principles of Neoclassical Environmental Economics, starts from the understanding that not all ecosystems are widely understood, making it incorrect to attribute monetary values that justify economic well-being to the detriment of the loss of bio- and geodiversity (Igari et al., 2020).

Thus, although the ecosystem services provided by caves are highlighted as a central object in this study, it is not a utilitarian view of the underground environment, but a starting point for organizing information on the current and future importance of this natural heritage, given its potential degradation. Even though the concept described here is based on the services provided by caves to human beings, it is understood that, as Ecological Economics puts it, all-natural heritage, whose assembly also incorporates caves, has an intrinsic value by its very existence yet little understood and therefore reserved for the future.

Historical review of ecosystem services

The concept of ecosystem services emerged in the late 1970s, after studies by Odum (1953), Wilson (1970), and Holdren and Ehrlich (1974), who renamed the concept of environmental services to "public service functions of the global environment", according to Mooney et al. (1997).

In the 1990s, when international conferences began to draw attention to global environmental threats, the topic began to gain more space in the media and consequently greater awareness in society. Seas, rivers, and biodiversity have finally come to be understood as fragile elements and human beings as polluting agents.

Although studies have discussed the terminology "ecosystem services" and their classifications since the late 1970s (Da Silva et al., 2018), it was in the late 1990s that the concept of attributing economic value to natural elements was presented. (Constanza et al., 1997). Using the term "natural capital", the authors proposed 17 services provided by nature that directly and indirectly benefit human populations. It is important to recall that in contrast to "natural capital", "built capital" represents all values related to economic well-being produced by human beings (Igari et al., 2020).

When calculated, these natural services related to "natural capital" accounted for an important part of what was called the economic value of the planet. The natural functions, or ecosystem services, defined by the authors for these calculations were: (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) pollution control 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 (Constanza et al., 1997).

This proposal for valuing the services provided by nature generated a great impact among technical and academic professionals and since then has been one of the most referenced articles in works on the environment (Imperatriz-Fonseca and Nunes-Silva, 2010). It is not by chance that several authors (Van Ree and Van Beukering, 2016; Da Silva et al., 2018; Andrade and Romeiro, 2009; Urban et al., 2022) highlighted the strategy of attributing economic values to services that nature provides human beings with great persuasive power, helping different political and social agents understand the conscious use of natural resources. According to them, communicating the evolutionary history of human populations, and connecting the present and future with the rest of nature, is an efficient path to better understanding and awareness of society with the conservation of the natural environment.

Another milestone on the topic was the Millennium Ecosystem Assessment, an action promoted by the United Nations (UN) in the early 2000s. The meeting was attended by more than a thousand scientists and advanced the conceptual discussion, organizing ecosystem services into four major axes: Regulation, Transport, Provision, and Culture (MEA, 2005). It was after the publication of the document originating from this meeting that the term "ecosystem services" effectively began to be addressed more broadly in different countries (McDonough et al., 2017).

Gray (2008) organized ecosystem services as intrinsic values of nature, defining five categories: Aesthetic, Economic, Functional, Scientific, and Educational.

In 2017, Ruppert and Duncan conceptualized these services in more detail, updating the term to direct and indirect, monetary and non-monetary benefits that human beings obtain from nature. The authors emphasize that, since human activities are a subject of action and modification of the services from which they benefit from, there is an urgent need to consider these relationships in economic and conservation strategies and analyses. In this way, ecosystem services should cover not only the biotic environment but the entire context in which they are inserted, such as the physical, economic, historical, and cultural environment.

Thus, this article adopts that ecosystem services are the direct and indirect benefits that natural elements offer to human beings, from support and well-being, to historical and cultural (Constanza et al., 1997; Daily, 1997; De Groot et al., 2002; MEA, 2005; Diaz et al., 2006; Farley, 2012). This approach is aligned with the principles of Ecological Economics, which associates all human economic activity, since its emergence, to the dependence on natural ecosystems (Cechin and Veiga, 2010).

Geodiversity Ecosystem Services

Although discussions about ecosystem services have evolved considerably over the last five decades, many authors still draw attention to the lack of an integrated approach in studies that largely discuss biodiversity services, neglecting the abiotic physical aspects involved (Van Ree and Van Beukering, 2016; Da Silva et al., 2018; Urban et al., 2022).

This dissociation may be related to differences in society's understanding and awareness of the concepts of geodiversity and biodiversity. Although biodiversity has gained more notoriety and understanding from different actors in society over the last few decades, the natural aspects of the physical environment — geodiversity — are still insufficiently understood and contemplated in the literature about their integrated services with the biotic environment (Gray, 2004, 2018; Brilha et al., 2018; Fox et al., 2020; Queiroz and Garcia, 2022).

Brouwer et al. (2013) place this difficulty as one of the greatest challenges in achieving a real economic dimension of these services for humanity. A disconnection that certainly results in incomplete analyses, compromising decision-making and strategies for the use and conservation of the natural environment (Van Der Meulen et al., 2016; Brilha et al., 2018). Claiming that the physical aspects of nature must be considered in these analyses, Gray (2005) proposed the term geosystemic services for goods and services provided by the abiotic environment to humans. The author started from the principle that life depends on nutrients, space, support, and favorable conditions for it to be established. These elements are part of a physical environment composed of rocks, rivers, soils, landscapes, and countless geological processes. In this regard, Brilha (2018), along with other authors (Stanley, 2000; Sharples, 2002; Gray, 2004, 2005; Fox et al., 2020), place geodiversity as the foundational support of all life on the planet.

In 2011, Gray proposed an update to the concepts of the Millennium Ecosystem Assessment for Geodiversity, defining its services as Regulation, Support, Culture, Provision, and Knowledge.

Gordon et al. (2012) and Lele et al. (2013) deepened this discussion with the proposal of the term "ecosystem services of nature", thus merging biodiversity with geodiversity. However, this union raises questions, as biotic and abiotic aspects differ fundamentally in their elemental characteristics across spatial and temporal scales (Van Ree and Van Beukering, 2016). To support this point of view, the authors referred to space as the characteristic of the physical environment in understanding not only the surface but also all flows and contributions from the subsoil with resources built over geological time. As for the time scale, it refers to the dimension of geological time and its collection of records about the history of the Earth, which contrasts with the dynamics of biotic ecosystems. There is a difference in approach, but one that, in a certain way, does not alter the unified thinking proposed by Gordon et al. (2012), given there have always been interrelationships between biotic and abiotic aspects throughout Earth's history, even within deep geological time (Barash, 2006; Benton, 2009; Stigall et al., 2019).

The categorization of geodiversity ecosystem services has also evolved as new discussions emerged (Gray et al., 2013, Gray, 2018; Brilha, 2017; Garcia et al., 2018). In a more recent publication, Brilha et al. (2018) categorize the ecosystem services of geodiversity into four functions: Regulation (atmospheric in the geosphere and hydrosphere), Support (soils, water, surface rocks, and internal rocks), Provision (nutrients, food and beverages, water, materials construction, industrial minerals, energy resources, and ornamental products) and Cultural (well-being and health, recreation, history, and knowledge).

A document published in 2020 by the World Commission on Protected Areas (MacKinnon et al., 2020) also draws attention to the interrelationships between biotic and abiotic environments, highlighting the interdependence between them (Crofts et al., 2021). According to the authors, creating guides for good conservation practices is a solution to breaking the hegemony of biodiversity and demonstrates that physical and biological aspects go together and are interdependent.

Fox et al. (2020) also contributed to this discussion by proposing a holistic vision of integration between biotic and abiotic aspects, whose common structure between biosystemic services and geosystemic services is called ecosystem services, or "geo-echo" services. According to the authors, services can be divided into geosystemic, solely abiotic, biosystemic, exclusively biotic, and intersection services, which can be guided by abiotic or biotic aspects. Water, for example, is a classic abiotic component, but it directs countless biosystemic and geosystemic services. Although they present this separation in theory, the authors highlight geodiversity as a fundamental aspect of the maintenance of ecosystem services, without which there would be no independent biodiversity in the real world.

In this context, caves can be understood as a complex system, in which the relationship between geodiversity and biodiversity is closely related. The gradual absence of light, which separates the cave into entrance, shadow, and aphotic zones, the physical and morphological characteristics of the cave, as well as the trophic resources (available food, such as plant material and guano, among others) directly influence the fauna present within it (Trajano and Bichuette, 2006).

Some research carried out in Brazil

Da Silva et al. (2018) proposed a bibliographic review of ecosystem services and found, in Brazil, few studies that integrate these services with aspects of geodiversity (Pereira et al., 2013; Da Silva and Nascimento, 2016; Santos and Bacci, 2017; Covello et al., 2017). The study concluded that it is up to the Brazilian scientific and academic community to carry out approaches to geodiversity using the organization of ecosystem services already widely adopted in biodiversity assessments and that, for this to occur, there needs to be greater dissemination of geodiversity and its role in nature's ecosystem services.

Garcia (2019) described the ecosystem services provided by geodiversity on the north coast of São Paulo. The study identifies 56 services distributed across 4 functions: Provision, Support, Regulation, and Cultural. The research reinforces the importance of identifying geodiversity ecosystem services in the construction of public policies for geodiversity management and in the communication of decision-makers.

Reverte et al. (2019) presented a method for identifying and evaluating geodiversity ecosystem services and their threats for the Taubaté Basin region (SP). The method considered quantitative analyses of abiotic aspects and also the cultural and historical aspects of the region. 53 services provided by geodiversity were identified, and distributed across four functions: Regulation, Support, Provision, and Cultural. The threats identified by human actions affect the supply of water, soil, and mineral resources, which also threaten certain species in the region (Reverte, 2020).

Balaguer (2022) carried out research on the ecosystem services of geodiversity, defining and evaluating them in the municipality of Caraguatatuba (SP), as well as evaluating the impacts on geodiversity and ecosystem services. The author identified 76 ecosystem services provided by geodiversity, distributed across the functions of Regulation, Support, Provision, Culture, and Knowledge. She also pointed out that the threats are mainly due to urbanization and the absence of vegetation, with the Support and Regulation functions being the most threatened.

Queiroz and Garcia (2022), through a literature review, warned about the low consideration of geodiversity in studies on ecosystem services.

There is also a scarcity in the national literature on geodiversity ecosystem services, which can increase the degradation of some sites and make their preservation difficult. As Reverte (2020) points out, urban growth corresponds to one of the main challenges to socio-environmental sustainability, causing impacts that compromise the integrity of geological heritage, natural resources, and the availability of ecosystem services.

Communication and comprehension

Urban et al. (2022) highlighted that by disregarding the interrelationships between human beings and geological elements throughout their past, present, and future, it becomes even more difficult to raise awareness among citizens regarding conservation issues of this natural heritage. According to the authors, the Earth, its structures, and processes must be approached as crucial elements for the development of civilizations, as well as for human economic history. An approach that proposes connecting geodiversity not only with the evolutionary history of civilizations but also with the current economy and its plans for the future.

By delving deeper into these relationships, according to Urban et al. (2022), the most understood ecosystem approach to the use of geodiversity is the economic provision of mineral resources (mining). This understanding arises, according to the authors, from the benefit directly linked to economic indicators and human development (industry, civil construction, technology). The second most understood approach is cultural value. Aspects related to religion, traditions, regional histories, and civilizations, such as archaeology, as well as aspects related to education and tourism, can be considered cultural values (Menin et al., 2022).

The authors propose (Urban et al., 2022), however, a necessary deepening of the topic with new direct and indirect approaches to the services provided by geodiversity to society. The study concluded that there is an urgent need for more research that characterizes geosystemic services clearly and simply, beyond just academic or scientific understanding, and more accessible to citizens.

Urban et al. (2022) also reinforced that the context of geodiversity must be divided into clear examples between caves, springs, landscapes, and other elements, even if the scientific value is not found in the first analysis. The reason for this consideration comes from the fact that many of them are of crucial importance in the development of human beings and therefore need protection.

From threats to conservation strategies

Understanding geodiversity as the physical basis for all ecosystems, threats to geodiversity can be understood as threats to the maintenance of life. Not all of these threats are caused by humans, but all of them influence life on Earth on different scales in some way. As Garcia (2019) highlights, impacts on geodiversity not only imply the permanent loss of scientific aspects related to the abiotic environment, but also threaten an entire biotic chain supported by this environment.

Large extinctions, dispersals, and biological events on a global scale, for example, have resulted in changes in geodiversity and its interactions with biodiversity, from volcanic events to climate change (Clack, 2007; Figueirido et al., 2012; Wilkinson et al., 2012; Zhang and Shu, 2014).

On the human time scale, the most relevant threats to geodiversity are natural erosion, the exploitation of geological materials, deforestation, the trade in fossils and minerals, inappropriate tourist use, real estate speculation, and urban growth, among others. In this sense, it is necessary to understand that, although geological processes are cyclical, losses in geodiversity can take thousands or millions of years to be re-established and are, therefore, not considered renewable on the human time scale. In this way, the loss of elements, interruptions of natural processes, pollution, among many other impacts on the physical environment, including the karst environment, must often be understood as irreversible (Souza-Silva et al., 2015; Mammola et al., 2019; Chiarini et al., 2022).

Impacts on geodiversity can be associated with great pressure for economic development and changes in land use policy (Garcia, 2019; Reverte et al., 2019; Reverte, 2020). Regarding caves, attempts to change protection regulations have been proposed in recent years in Brazil, leading to criticism and mobilization by experts, as well as national and international academic and speleological institutions (SBE, 2020).

Whatever the use of the physical environment, the most fundamental principles in conservation guide us to carry out prior inventory, characterization, and qualification work on the sites present (Serrano and Ruiz-Flaño, 2007; Pereira et al., 2013; Brilha, 2016; Garcia et al., 2018; Santos, 2019). Qualitative and quantitative assessments of ecosystem services can inform better policy decisions (Preston and Raudsepp-Hearne, 2017). As an example, adequate planning for the use of specific areas, regulatory analyses, environmental damage assessments, and environmental management and conservation instruments stand out.

In this sense, over the years, different inventory methods and diagnostic mechanisms have been developed, including those related to speleological heritage. These works sought to characterize natural elements and also raise risks of degradation, fragility, vulnerability, and protection indicators (Pereira et al., 2013; Forte et al., 2018; Menin and Bacci, 2022).

In short, these studies seek to choose the representation of elements at different scales — local, regional, and global — to afterward define strategies that better guide their use and conservation (Menin and Bacci, 2022). Given the dependence of human beings on the consumption of natural resources for their development, it is not necessary to completely give up on natural resources but to seek balanced development in line with awareness, conservation, and sustained development actions (Da Silva et al., 2018).

Caves in the context of ecosystem services

The word karst comes from a region with carbonate rocks between Italy and Slovenia known as Kras (currently called Karst). It was the first region with caves studied scientifically, becoming a reference in a typical landscape in carbonate rocks (Williams, 2008). Currently, the term karst, as well as karst landscape, refers to characteristic elements of carbonate rocks with scarps, outcrops, sinkholes, canyons, blind valleys, and caves. When approaching karst ecosystem services, it is understood that this entire set must be considered in the analysis and not just the underground environment itself.

Caves and karst can be considered environments with different direct and indirect services provided to humans (Urban et al., 2022). As they are an occurrence with geological and geomorphological features such as speleothems, paleofloors, terraces, sediment, and fossil deposits, in addition to aspects related to endemic life, they are also considered as an element of geodiversity with known or potential scientific value (Woo and Kim, 2018). Especially because they are underground environments of difficult access, caves are often partially explored, and, therefore, their scientific potential is not yet widely known (Woo and Kim, 2018). Urban et al. (2022) also draw attention to caves as an important geological occurrence. Its geomorphological aspects, according to the authors, provide scientific information indicating age and formation processes. The authors also make a connection between underground abiotic aspects and biotic ones, including the recreation of paleoenvironments. Speleothems conduct scientific geochemical studies that connect with different areas of knowledge. Research has associated the oxygen and carbon isotopes found in speleothems with the reconstruction of the past climate and paleoenvironments, associating caves with the history of human occupation and the presence of different faunas (Lauritzen and Lundberg, 1999; Auler and Smart, 2001; Cruz et al., 2005; Auler et al., 2006; Stríkis et al., 2011; Della Libera et al., 2022). Admittedly, Van Ree and Van Beukering (2016), when discussing the cultural services provided by geodiversity, used the example of caves as a relevant provider of historical-cultural services associated with human occupation.

Based on these examples, and although Urban et al. (2022) do not delve into the speleological environment, the authors pointed to caves as providers of ecosystem services related to the Provision, Scientific, Cultural, and Educational values. The authors also added that caves in non-carbonate rocks also fit into this context, since the morphologies add important geological information about the regions where they are located, regardless of the type of rock in which they are formed.

In Brazil, the definition of speleological heritage includes the set of biotic and abiotic, socioeconomic, historical-cultural surface or underground elements that represent and are associated with the natural underground environment (BRASIL, 2004). In other words, caves and the external elements associated with them are understood as part of this heritage and, therefore, assume numerous interrelationships with human beings. Although this definition does not refer to ecosystem services, the broad understanding of speleological heritage adopted in the country considers the interrelationships between human beings and the natural environment.

CATEGORIZATION OF ECOSYSTEM SERVICES PROVIDED BY CAVES

In this study, we chose to categorize the ecosystem services provided by caves based on geodiversity value models proposed by Gray et al. (2013) and by Brilha et al. (2018). The authors divide these values into four groups:

- Regulation, which includes atmospheric and hydrological issues;
- Support, which refers to soils, waters, surface, and internal rocks;
- Provision, which refers to nutrients, food and beverages, materials and minerals, and energy resources;
- Cultural, which chooses scientific, educational, cultural, historical, and tourist values.

From a bibliographical survey and based on this division of functions presented by the authors, the ecosystem services provided by caves were categorized (Table 1). Each of the groups was divided according to the nature of the service provided.

The bibliographic review considered online search tools on the Google Scholar platform for scientific journals and technical publications involving speleology. The descriptors researched were "ecosystem services, speleology, caves, speleological heritage".

Articles related to ecosystem services without examples related to the speleological environment were not considered, as well as articles related to the underground environment without direct or indirect mention of ecosystem services. After the analysis, 36 articles published in national and international scientific journals, conference annals, master's dissertations, and doctoral theses were selected. The examples found in the publications were summarized and organized into analysis categories, justifying the characterization of each ecosystem service.

Once the ecosystem services provided by caves were identified in the literature, the same method of bibliographical survey and organization of information was carried out for Devil's Cave (DC). Also called Gruta da Tapagem, the old name is due to the Blind Valley of the Tapagem River, which enters the cave (Cordeiro, 2013). DC is located in Devil's Cave State Park, in the southern region of São Paulo state. The cave was chosen as a result of its collective evaluation during a cave inventory and qualification study (Menin and Bacci, 2023), which positioned it as the best evaluated among a list of 79 main caves in the region. The survey and organization of the services and functions provided by this particular cave were carried out by assigning a grade to each service according to the quantity and relevance of the examples found in the bibliographical survey. Therefore, it was possible to assign quantitative values for a preliminary analysis of the ecosystem services provided by DC to society. For this analysis, a scale with values from 0 to 5 was assigned to each ecosystem service classification

Table 1. Grouping and characterization of ecosystem services provided by geodiversity proposed by Gray et al. (2013) and by Brilha et al. (2018).

Function of ecosystem services of geodiversity	
a. Regulation	Hydrological regulation
	Biotic regulation
	Regulation of external ecosystems
b. Support (Soils, water, surface rocks, and subsurface rocks)	Hydrological support
	Landscape elements
c. Provision (Nutrients, food and beverages, water, building materials, industrial minerals, energy resources, and ornamental products)	Water provision
	Provision of raw materials
	Shelter provision
	Indirect environmental and economic values
	Economic industrial biological potential
d. Cultural (Well-being and health, recreation, historical and knowledge)	Scientific value
	Cultural value
	Historical value
	Prehistoric and archaeological value
	Educational and knowledge value

corresponding to the number of examples found in the literature. The referred scale and justification for the score are presented in Table 2.

RESULTS AND DISCUSSION

The quantitative analysis carried out based on examples found in the literature made it possible to identify the direct and indirect ecosystem or "speleosystemic" services provided by caves. When using the classifications proposed by Gray et al. (2013) and by Brilha et al. (2018), we observed that some examples of these services can operate in different classifications of the aforementioned methods (Regulation, Support, Provision, and Cultural).

An analysis of the identified services allowed us to suggest that caves, in general, have a greater influence on Provision and Cultural functions, but their Support and Regulation functions should not be disregarded. No geographic order of magnitude analyses were carried out, but it is understood that most of these services have local and regional influences.

As previously stated, different researchers affirm that caves represent an environment that has been insufficiently investigated. In this context, there is also the potential to provide yet unidentified ecosystem services, for instance, industrial uses of biological research carried out using bacteria found in underground environments (Mushtaq et al., 2021). In this case, the influence of this service has the potential to go beyond regional limits reaching national and even global scales once incorporated into industrial chemical solutions.

In quantitative terms, the number of examples found allowed us to identify the weight of each axis according to the classification between Regulation, Support, Provision, and Cultural (Gray et al., 2013; Brilha et al., 2018) provided by the caves. Figure 1 shows a quantitative overview of the distribution of these services, and Table 3 is

Table 2. Calculation is used to assign a quantitative value to examples of ecosystem services provided by Caverna do Diabo. Source: Prepared by the authors.

Value	Justification
0	No examples were found in the literature search.
1	A single example was found.
2	Up to 2 examples were found.
3	Up to 3 examples were found.
4	More than 3 examples were found.
5	There are numerous examples or the cave is notably referenced in the aspect evaluated.

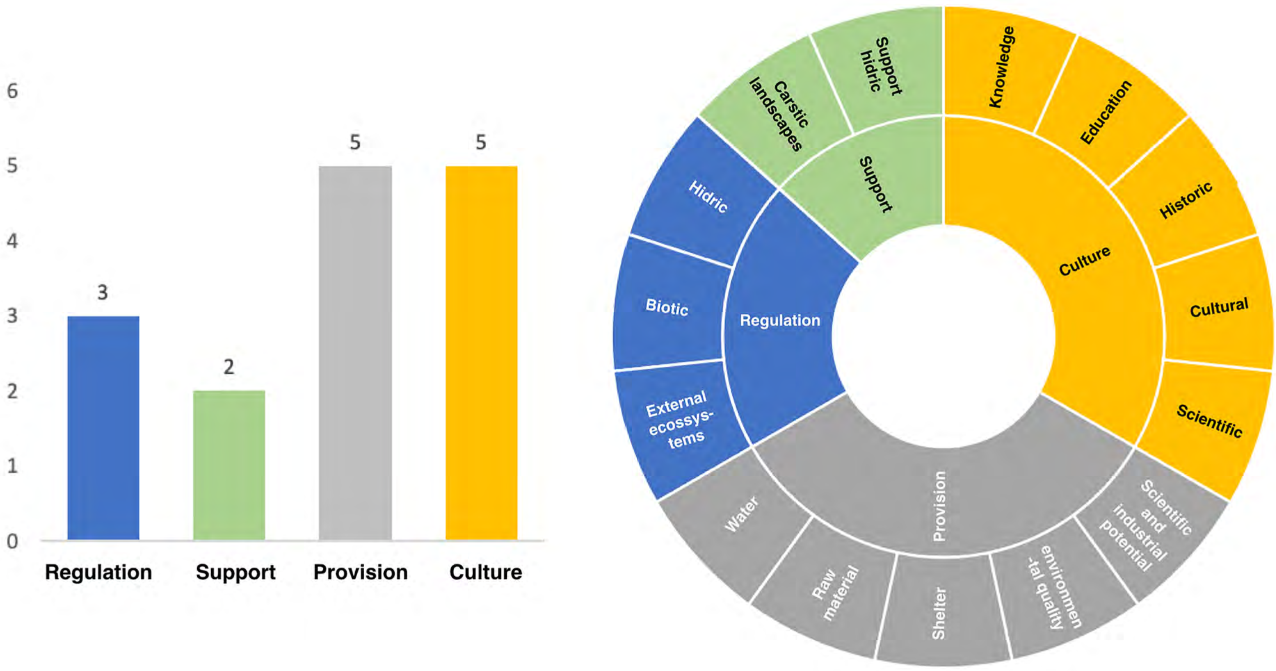

Figure 1. Graphic representation of the ecosystem services provided by caves, here also called "speleosystemic services". The colors represent the grouping proposed in Table 3.

Table 3. Organization of geosystemic or "speleosystemic" services presented by caves, with a summary of examples found in the literature following the grouping proposed by Gray et al. (2013) and Brilha et al. (2018).

Function	Group	Examples of services provided by caves
a. Regulation	hydrological regulation	Regulation Hydrological regulation Karst aquifers contribute to the availability and quality of groundwater in a given region. Drainage in karst functions as a collector and high-speed transporter, aiding in the distribution of water between different recharge and discharge zones (Travassos, 2019). The transport of water, along with its physicochemical properties, also contributes to the dispersion of a multitude of microbiological organisms that are still poorly studied (Medellin et al., 2017).
	Biotic regulation	In the biotic environment, hundreds of studies on underground biology are published every year, which demonstrates that caves encompass a still largely unexplored universe, and consequently, without a comprehensive understanding of the true extent of their biological ecosystemic significance for humans. Internal and external faunas may be associated with caves as shelter environments and nutrient providers.
	Regulation of external ecosystems	Some classic cases are better known, such as the indirect biotic regulation represented by caves as habitats for bats, which, in turn, assist in pest regulation, pollination, and seed dispersal, thus contributing to reforestation and botanical dispersion for kilometers around their original habitats (Leal and Bernard, 2021; Kunz et al., 2011; Medelin et al., 2017; López-Hoffman et al., 2017; Wiederholt et al., 2013). In addition to their contribution to external biotic regulation, bats play a critical role in the biotic regulation of underground ecosystems by carrying nutrients through guano, the foundation of the food chain for a multitude of other smaller organisms (Pimentel et al., 2022). Studies have calculated the economic value of ecosystem services provided by bats, which can also be directly associated with caves (Kunz et al., 2011).
b. Support (Soils, water, surface rocks, and subsurface rocks)	Hydrological support	Support, storage, and transport of groundwater (Travassos, 2019).
	Landscape elements	Karst terrain with lapiaz, towers, canyons, blind valleys, sinkholes, and outcrops.
c. Provision (Nutrients, food and beverages, water, building materials, industrial minerals, energy resources, and ornamental products)	Water provision	As previously mentioned, water storage and transport provide various services to the environment and humans in karst regions.
	Provision of raw materials	Caves have been venues for saltpeter extraction for gunpowder production; currently, karst areas are subject to raw material extraction for construction and consumption industries (limestone).
	Shelter provision	Shelter for endemic species.
	Indirect environmental and economic	Caves are among the geological features most utilized for tourism. It is estimated a global volume of 70 million cave tourists, generating over 7 billion Euros annually (Chiarini et al., 2022). Tourism in the karst environment is also linked to the appreciation and increased awareness of the natural surroundings.
	Economic industrial biological potential	Recent studies have been published associating the biotic environment existing in the underground with potential industrial use of significant impact. Mushtaq et al. (2021) demonstrate the presence of actinomycetes in caves, antibacterial agents with great industrial utility yet to be fully explored; In another case, the discovery of fungi in caves entails potential industrial use for fermentation more efficiently than current processes (Paula et al., 2019); Plastic biodegradation is also efficiently carried out by fungi within caves, indicating promising research in this direction (Mazina et al., 2019).
d. Cultural (Well-being and health, recreation, historical and knowledge)	Scientific value	Scientific research associated with studies of climate, geology, biology, archaeology, and paleontology.
	Cultural value	Caves feature cultural and regional issues related to festivities, beliefs, and regional legends, which in turn also reflect on direct and indirect economic activities.
	Historical value	Caves often encompass regional historical passages (mining, use, and exploitation) or even speleological ones.

Photo: Daniel Menin.

Figure 2. Example of the Cultural Group (d). Scenic beauty can be related to cultural value, well-being, recreation, and tourism. Janelão Cave, Peruaçu Caves National Park.

Photo: Daniel Menin.

Figure 3. Example of Regulation (a), Support (b), and Provision (c) Groups related to the storage, transport, supply and quality of groundwater. Gruta do Impossível, Iraquara, Bahia.

Photo: Daniel Menin.

Figure 4. Example of the Cultural Group (b) related to the scientific value associated with geology and paleoclimatology resulting from the dating of speleothem samples. Toca da Boa Vista Cave, Campo Formoso, Bahia.

Photo: Daniel Menin.

Figure 5. Example of Cultural Group (b) related to the scientific value associated with evolutionary biology and underground fauna. Fendão Cave, Intervales State Park, Capão Bonito, SP.

Photo: Daniel Menin.

Figure 6. Example of the Cultural Group (b) related to the scientific value associated with the presence of fossils. In this example, the bones of a monkey found in Toca da Barriguda, in Campo Formoso, Bahia.

a descriptive panel with a summary of examples found in technical and academic bibliographical research.

The Devil's Cave characterized by its "speleosystemic" services

Based on the function of geodiversity ecosystem services presented in Table 1 and the valuation calculation presented in Table 2, a quantitative analysis of the services provided by the Devil's Cave was carried out (Table 4).

The examples were counted directly and indirectly. They are, therefore, independent of related publications specifically about the Devil's Cave (direct), but also include generic examples that apply to the cavity (indirect). This is because some examples may not have been the direct result of studies and publication about that cave, but can be applied to it generically. The Regulation service for external ecosystems provided by bats, for example, is a case that has not yet been

Photo: Daniel Menin.

Figure 7. Example of the Cultural Group (b) related to the scientific value associated with historical and cultural aspects. Precarious structures for locomotion and saltpeter extraction are observed in a cave in the region of Natalândia, MG.

specifically studied on Gruta da Tapagem. However, it was considered that the cave notably harbors colonies of this mammal.

Columns 1 and 2 represent the organization of information according to the classification used. Column 3 presents a description of the service specifically provided by CAD. Column 4 applies a calculation for quantitative evaluation and column 5, the references considered specifically for the Devil's Cave (direct references).

From the data collected, the cultural importance of the Devil's Cave stands out, which can be explained by its tourist and educational uses, in addition to its relevance in the science and history of the region. It is also possible to observe that some examples can be positioned in more than one function according to the approach adopted. The application of DC suggests that services can change from cave to cave depending on their intrinsic characteristics and, mainly, the level of knowledge they have about them.

Figure 12 shows a quantitative survey of examples of services directly or indirectly associated with the Devil's Cave grouped according to the organization of functions adopted in this study (Gray et al., 2013; Brilha et al., 2018).

Photo: Daniel Menin.

Figure 8. Example of the Cultural Group (b) related to the scientific value associated with archaeological aspects. Cave paintings at cave entrances in Cavernas do Peruaçu National Park, MG.

Photo: Daniel Menin.

Figure 9. Example of the Cultural Group (b) related to the scientific value associated with cultural, tourist, and religious aspects. Church built inside the Mangabeira Cave, in Ituaçu, MG.

Photo: Daniel Menin.

Figure 10. Example of Cultural Group (b) related to tourist and recreational aspects. A family making use of the structure and tourist visitation in Caverna do Diabo, SP. Tourism represents an important part of the local economy.

Photos: Daniel Menin.

Figure 11. Examples of the Cultural Group (b) related to educational aspects. Students from the public school system in Sumaré (SP) create a model explaining aspects of the karst relief and a cave inside the school covering different areas of knowledge.

The chart also highlights the cultural relevance of the Devil's Cave as the main set of services provided by the cave. This grouping includes the entire set of services related to Tourism, Education, and Recreation, in addition to Historical, Social, and Scientific aspects. Given it is a State Conservation Unit, the cave currently has a structure for visitation and research support, which certainly contributes to the survey of examples of services provided by the Cultural function.

In the Provision function, the second best-evaluated value, is services related to the local economy, since tourist visits contribute to an entire ecosystem of local and regional services, such as the existence of environmental drivers, ecotourism agencies, inns, restaurants, and indirect attractions such as trails and waterfalls. Still in provision are aspects related to the local fauna and the importance of the Tapagem River, which runs through the cave and contributes to local water distribution. In terms of Support and Regulation functions, examples related to the regional karst landscape with valleys, cliffs, rivers, and, respectively, water, biotic, and external ecosystem regulation stand out, since the cave is located in a conservation unit in the middle of all the biodiversity of the Atlantic Forest.

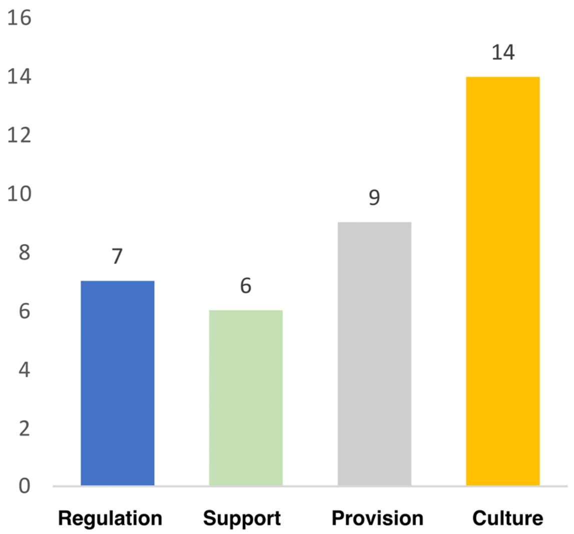

Figure 12. The quantitative scale of services provided by CAD. The numbers represent the number of examples found within each function presented.

FINAL CONSIDERATIONS

Caves have always provided important services to human populations throughout evolutionary history, which also includes the present and the future. These services are independent of the conceptual point of view and called biotic or abiotic, ecosystem, geosystemic, or nature services.

The application of the analysis method described here to Devil's Cave suggests that knowledge of services can vary greatly according to the knowledge one has about a given cave. This indicates that the most appropriate analysis for framing the ecosystem services provided by caves must be carried out in a generic and, sometimes indirect, manner, taking care when applying the method to individual caves. As the survey of services is based on knowledge already acquired, caves that have been little studied may be under-evaluated.

Having a good definition of the interrelationships between humans and caves allows the development of indicators and qualification mechanisms, as well as the establishment of more appropriate conservation, education, and dissemination measures. The analyses described here allow us to affirm that the caves have high cultural potential, which includes services related to science, education, tourism, and

Table 4. Grouping of examples of ecosystem services found in a bibliographic survey on caves.

Function	Group	Devil's Cave (DC)		
		Examples of services provided by DC	Number of bibliografic references	Scientific articles about DC
a. Regulation	hydrological regulation	The water system of Tapagem (Devil's Cave) is an important hydrological recharge area for the region, involving drainage systems such as the Ostras River, Pardo River, and Ribeira River.	2	(Cordeiro, 2013; Sallun et al. 2015)
	Biotic regulation	Studies on fauna and bat colonies indicate an influence on internal biotic regulation and potentially external regulation.	3	(Bichuette et al., 2015; Watanabe et al., 2016; Campos-Filho et al., 2022)
	Regulation of external ecosystems	Bat colonies and water transport from the Blind Valley of Tapagem to the Ostras River may indicate regulation of external ecosystems.	2	The examples here were indirectly applied.
b. Support (Soils, water, surface rocks, and subsurface rocks)	Hydrological support ion	Tapagem River,	1	(Sallun et al., 2015)
	Landscape elements	Karst of the Devil's Cave State Park, scenic and speleometric aspects of the cave.	5	(Silverio, 2015; Aguiar, 2017; Sallun et al., 2015)
c. Provision (Nutrients, food and beverages, water, building materials, industrial minerals, energy resources, and ornamental products)	Water provision	Tapagem River.	1	(Sallun et al., 2015)
	Provision of raw materials	Not listed.	0	n/c - Não se tem registro da provisão de matérias primas a parte da Caverna do Diabo.
	Shelter provision	Shelter for subterranean fauna.	3	(Bichuette et al., 2015; Watanabe Et al., 2016; Campos-Filho et al., 2022)
	Indirect environmental and economic values	Touristic, sports, and recreational activities, and economic influence on regional communities, including the quilombolas.	5	(Silverio, 2015; Aguiar, 2017; Menin e Bacci, 2023)
	Economic industrial biological potential	Biological studies in the cave indicate the existence of subterranean fauna, and although there are examples of the industrial economic potential of biological studies in caves, no applications were found from the Devil's Cave.	0	No indirect examples can be attributed in this case
d. Cultural (Well-being and health, recreation, historical and knowledge)	Scientific value	Paleoclimatic, geological, biological, impact, and carrying capacity studies.	5	(Mira et al., 2021; Bichuette et al., 2015; Watanabe et al., 2016; Campos-Filho et al., 2022; Salum et al., 2015; Araujo et al., 2003)
	Cultural value	High regional linkage.	3	(Menin e Bacci, 2023; Silverio, 2015; Aguiar, 2017)
	Historical value	Rich regional and speleological history.	1	(Figueiredo et al., 2007)

social. Tourism, in particular, provides economic services to surrounding communities and conservation units. Furthermore, it also represents an important means of scientific communication, especially if associated with information about the services provided by speleological heritage to society, which does not yet seem to be well embraced in Brazil.
In some cases, the ecosystem services provided by caves can go beyond the local and regional spheres, representing global relevance given the potential for new studies and scientific discoveries.
Therefore, the organization of ecosystem services provided by caves, which could also be called "speleosystemic services", can function as a guide for educational and scientific dissemination projects, helping to group information, identify pedagogical opportunities, and create complementary teaching sequences and interdisciplinary.
Finally, this compound helps to bring speleology closer to the lay public and government agents, making them better understand the areas of knowledge involved in the study of caves and the importance of conserving speleological heritage. Investing in knowledge and conscious use of this environment represents not only bringing society closer to the most varied areas of knowledge but also stimulating science itself and the conservation of speleological heritage in the present and for the future.

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