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ORIGINAL ARTICLE

The Educational Importance of Geosites Representing Geodiversity-Biodiversity Relationships: A Thematic Inventory Proposal

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Abstract
The relationships between geodiversity and biodiversity are a topic of growing relevance. Understanding these relationships in different contexts and scales has the potential to increase conservation efforts, especially considering climate and environmental changes. Exploring this topic in educational activities is a way to make it more accessible to the society. Considering the relevance of geosites for education, the present work proposes a thematic inventory of geosites representing relationships between geodiversity and biodiversity. With the use of a descriptive file and a classification scheme, the proposal was applied in the project Geopark *Costões e Lagunas* (Cliffs and Lagoons), in Rio de Janeiro, Brazil. 19 geosites were identified, described, and classified, embracing different situations, and allowing approaches on several issues such as spatial and temporal scale of the relations, the influence of the diversity of elements or of specific elements, degradation risks etc. The results are intended to be applied to the educational activities that already take place in the geopark project but also to be an incentive for similar initiatives in other areas, contributing to the dissemination of the topic of relationships between geodiversity and biodiversity.

Keywords Geoeducation · Natural diversity · Geoconservation · Geopark

Introduction

Studies on the links between geodiversity and biodiversity have been growing in importance worldwide and most of them indicates a positive relationship (Tukiainen et al. 2022). Geodiversity is recognised as a driver of biodiversity since the physical environment provide the necessary conditions for the development of biological elements (Gray 2013; Lawler et al. 2015). However, the application of the concept of geodiversity in ecological contexts is a topic that needs improvement since issues such as development of methods to assess geodiversity at different scales and in different regions, and the need of unified approaches to assess both geodiversity and biodiversity are still challenges that need to be tackled (Tukiainen et al. 2022). Although there is a tendency of positive relationships, they are complex and may occur quite differently across scales and depending on the environment.

Despite the inherent links between geodiversity and biodiversity, and the acknowledged role of geodiversity in determining biodiversity distribution patterns, nature conservation efforts are mostly directed towards the protection of biological elements, with minor attention to the physical environment (e.g. Matthews 2014). Recent works have been trying to change this scenario. The idea of Conserving Nature's Stage (CNS) is an example of how geodiversity can be integrated into biodiversity conservation. According to Beier et al. (2015), the beginning of the CNS approach is the work of Hunter Jr et al. (1988), which stated that the physical environment should be used as a surrogate to protect biodiversity, working as a coarse filter.

The CNS approach is based on a metaphor that the species are actors playing on a stage, which is the physical environment (Anderson and Ferree 2010; Gordon et al. 2022). The play can only happen if the actors have a stage. In other words, in order to conserve biodiversity, it is crucial that

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geodiversity must also be target of conservation strategies. Considering that biodiversity has been the main target of conservation efforts, strategies to include geodiversity as a fundamental part of nature need to be developed in different "fronts", including education.

Studies demonstrating the relevance of geosites for education are relatively common. Numerous methods for inventory and evaluation of geosites include the educational value (or potential educational use) as an important part of the process (e.g. Serrano and González-Trueba 2005; Bollati et al. 2016; Brilha 2016; Reynard et al. 2016; Santos et al. 2020). Some studies present interesting thematic approaches. Coratza and Waele (2012), for instance, highlight the didactic relevance of geomorphosites representing processes related to natural hazards. These geomorphosites can be tools for geo-environmental education that can be widely used to educate the society about the topic of natural hazards and their effects. Another thematic study was presented by Clivaz and Reynard (2018), that focused on "invisible" geomorphosites, which are sites representing human modifications on landforms. The authors state that some geomorphosites may have been destroyed or hidden by human activities, but they also play an important role for being representative of the alterations, being interesting targets for geotourism and educational activities.

There are also studies indicating the importance of the ecological value for the assessment of geosites, as part of the scientific value or as an additional value. Panizza (2001) introduced that the ecological support role of geomorphosites, that may be related to exclusive habitats, should be part of the assessment of the scientific value. The same rationale is followed by Bollati et al. (2015), which evaluated the ecological support role as part of the global value of a glacial geomorphosite and highlighted that vegetation was used in several studies as a tool to analyse glacier dynamics. Reynard et al. (2016) utilise the ecological value as an additional value in their assessment proposal, focusing on the importance of geomorphology in the establishment of habitats and in situations where geomorphological features are protected due to ecological reasons.

The objective of this work is to present a thematic inventory focused on the relationships between geodiversity and biodiversity as a strategy to enhance educational activities related to this topic. It was developed in the area of the Geopark *Costões e Lagunas* (Cliffs and Lagoons) project, which is not (yet) an UNESCO Global Geopark (UGGP) but has been developing several educational activities in its territory for more than a decade. Geoparks have an important role in promoting education in geosciences and in the achievement of the United Nations Sustainable Development Goals (Catana and Brilha 2020). Creating a thematic inventory focused on the relationships between geodiversity and biodiversity for the Geopark *Costões e Lagunas*, which is intended to become an UGGp in the future, is an effort to strengthen educational activities in the territory and to contribute for the recognition of geodiversity as fundamental in nature studies, especially in nature conservation contexts. The success of this initiative is intended to encourage other areas to do similar activities.

Study Area

The Geopark *Costões e Lagunas* embraces 16 municipalities in south-eastern and eastern coasts of Rio de Janeiro State, SE Brazil (Fig. 1). The project has been active since 2010 and, since then, several initiatives to consolidate the geopark are being developed.

The area hosts a high geodiversity, from coastal massifs composed of rocks from the Proterozoic to coastal sand barriers developed during the Holocene. The coastal massifs are related to tectonic events that took place after the breakup of Gondwana and the opening of the Atlantic Ocean. Rifting processes were responsible for the generation of mountain ranges parallel to each other and to the ocean, being divided by valleys (hemigrabens) (Zalán and Oliveira 2005). There are also two alkaline massifs (*Cabo Frio* Island and *São João* Hill) formed by the presence of a possible hotspot that generated magmatic events during the Cenozoic (Thomaz-Filho et al. 2005). Besides that, rocks in the region register a very important geological event: the amalgamation of the palaeocontinent Gondwana. As described in Schmitt et al. (2016), the event known as *Búzios* Orogeny took place between the Cambrian and the Ordovician and was the last orogenetic process related to the formation of the continent.

Besides the coastal massifs, the area is characterised by the presence of large coastal plains and several coastal lagoons, highly affected by sea-level variations during the Quaternary (Martin et al. 1996). The south-oriented coastline has a double barrier-lagoon system in which the inner barrier was formed in the Pleistocene and the outer barrier, in the Holocene. A major lagoon (*Araruama* lagoon) is located in the backwards of the inner barrier, being one of the most important geological features of the area. The northern portion is marked by large sedimentary deposits of marine and fluvial origin, since the area is affected by the *Paraíba do Sul* River, the biggest river in the State of Rio de Janeiro. A wave-dominated delta was formed in the area and the geomorphological setting is characterised by beach ridges with different ages (Rocha et al. 2019).

The area of the geopark project is recognised not only by its geodiversity. The southern portion has the presence of the Cabo Frio Centre of Plant Diversity, an important biodiversity hotspot in the Neotropical region. There are several

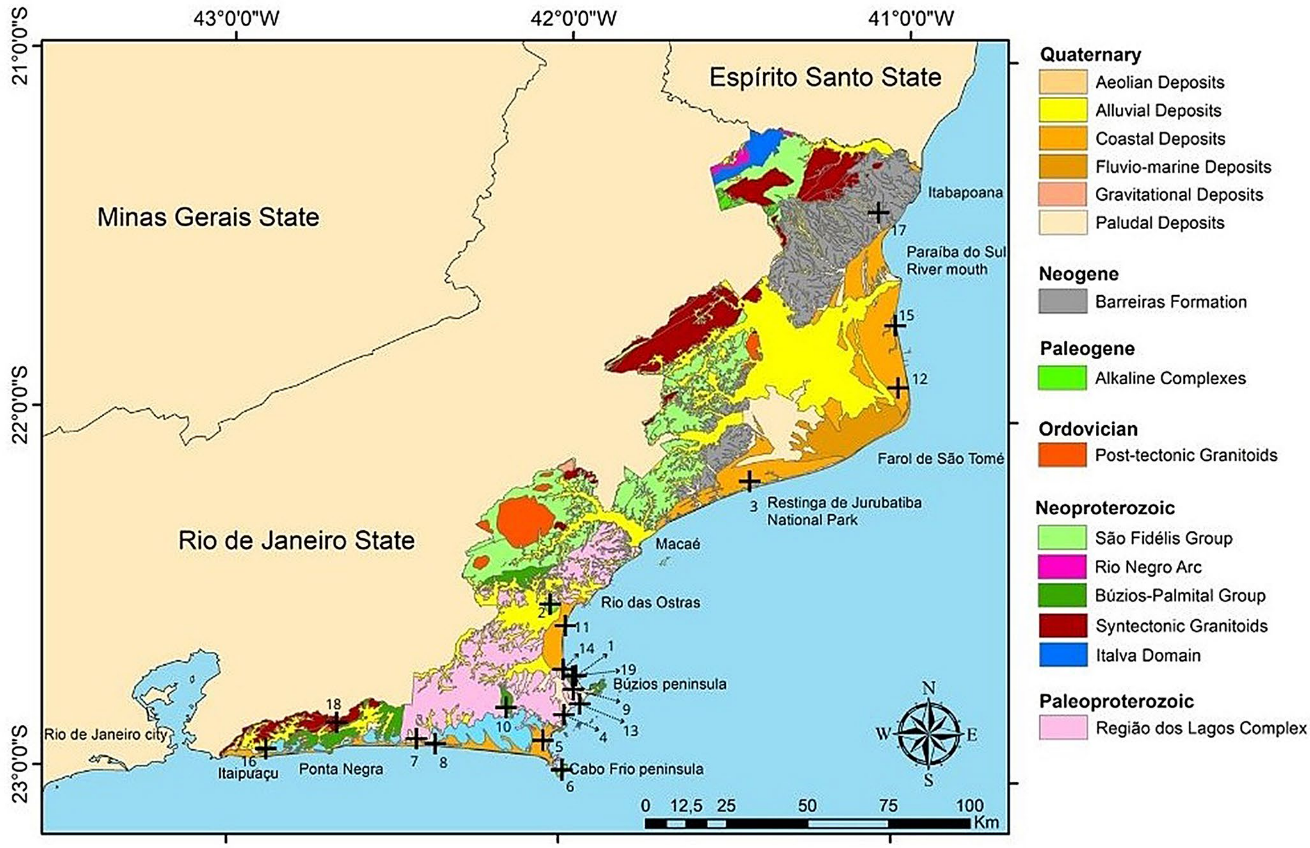

Fig. 1 Simplified geological map of the Geopark *Costões e Lagunas* and location of the geosites described in the manuscript. See Table 1 for name and description of the geosites

Table 1 Parameters to describe the geosites

-geosite name-
Localisation
Geodiversity
Biodiversity
Geo-Bio relationships
Spatial scale
Temporal scale
Risks and degradation

endemic species and unique plant communities (Bohrer et al. 2009). This occurrence is strongly related to the geological setting and to the fact that the area is marked by a climatic peculiarity, being dryer than the surrounding areas.

Another important area is the *Restinga de Jurubatiba* National Park, where coastal barriers originated during the Pleistocene separated by lagoons with different water compositions create conditions for the setting of a high diversity of sandbank vegetation species which are part of the Atlantic Rainforest (Santos et al. 2004). This vegetation is severely degraded due to economic activities since the colonial times and protected areas such as the cited national park are of fundamental relevance to protect the remaining forests.

Therefore, the area of the geopark project presents a high geodiversity, registering several geological events with different ages, and this geodiversity is highly connected to the biodiversity, which also presents peculiarities when compared to other areas in southeast Brazil. It makes it an interesting place to investigate the educational value of geosites representing such connections.

Methodological Procedures

Considering that the objective of this research was to create an inventory focused on educational use, the methods were based on qualitative evaluation of the geosites. Quantitative evaluations were not considered necessary since the focus was the identification of geosites and the description of parameters related to the relationships between geodiversity and biodiversity, which was considered enough for the proposed use of the inventory.

The main criteria for selecting geosites were their educational potential, together with use and management issues, namely accessibility and safety. In this study, the educational potential was represented by the representativeness

Table 2 Classes representing the types of interactions identified

Type of interaction	Class description	Educational objective
Natural diversity	Natural diversity is understood as the combination of geodiversity and biodiversity. This class represents interactions where higher geodiversity is directly related to higher biodiversity.	Analyse and discuss the concepts of geodiversity, biodiversity and natural diversity, highlighting systemic interactions.
Specific elements	Represents situations where specific characteristics of the abiotic environment are related to specific occurrences in the biotic environment.	Demonstrate the relevance of specific abiotic elements for the development of specific biotic features, not focusing on the diversity, but on the elements themselves.
Large-scale relationships	Represents connections between the abiotic and biotic environments related to large-scale elements, such as mountain ranges, coastal plains, fluvial valleys etc.	Analyse situations where the relationships happen in large spatial scale, allowing, for instance, approaches on the concept of beta diversity.
Temporal relationships	Represents the temporal relations between abiotic and biotic environments, which is specifically relevant when dealing with environmental changes, such as the ones related to global warming.	Discuss the temporal variability of natural elements, introducing concepts such as enduring features and focusing on the dynamics of different environments.
Uncommon relationships	Represents uncommon situations, where the relationships between abiotic and biotic elements leads to the development of unique environments.	Demonstrate that, in some cases, the relationships between abiotic and biotic elements generate unique environments, which are relevant due to its representativeness and rarity.
Environmental impacts	Represents situations where environmental impacts affect the relationships between abiotic and biotic elements, which could lead to ecological imbalances.	Discuss the importance of integrated analysis of the environment in order to better comprehend and avoid/minimise impacts.

of geodiversity-biodiversity interactions, based on the ideas of ecological support role and CNS. Since this inventory is intended to be used directly by organisers of educational activities (university professors, school teachers, geotourism professionals etc.), only geosites with high representativeness were selected, in an attempt to enhance the interpretive potential of the inventory.

The geosites were identified through bibliographic review embracing research articles, thesis and dissertations, and documents from the several Protected Areas present in the region. The knowledge of the region by the authors was also relevant in the selection of sites. It may be seen as subjective, but the authors have been working in the area for more than a decade, so their knowledge naturally played an important role in this step of the work. The main criterion for the selection was the representativeness of interactions between the abiotic and biotic environments.

More research on different topics is being developed in the geopark area, which is expected to be responsible for the identification of new geosites to be included in the inventory, especially in the northern portion, where a small number of geosites was identified.

Geosites Description

Each geosite was described according to the parameters displayed on Table 1. First, geodiversity and biodiversity are described separately, in order to provide specific information on physical and biological elements, and only then comes the description of what relationships can be observed in the geosite.

The relationships occur in different spatial and temporal scales, so it was interesting to include these parameters in the assessment. The description of the spatial scale is important because, in some cases, there is a very specific relationship that occurs in local or even microscales, representing the importance of particular elements. In other cases, the relationship occurs regionally, usually involving several physical and biological elements. The temporal scale is relevant because the interactions between geodiversity and biodiversity occur in a period, and the extension of this period depend on the environmental factors involved, which is an important fact to be highlighted. For instance, sandbank vegetation occupying Holocene coastal barriers have different temporal relationships when compared to the semideciduous seasonal forest occupying the tablelands developed in Neogene sedimentary rocks.

Finally, the existence of risks of degradation or even current processes of degradation were included for its relevance within educational contexts. In this case, the analysis was focused on how human activities may be responsible for impacts on systemic interactions between physical and biological elements, highlighting that impacts on some of these elements can result in impacts on other elements, not directly related to the degradation process itself. The fact that natural processes also represent risks to geosites (e.g. García-Ortiz et al. 2014; Pelfini and Bollati et al. 2014; Selmi et al. 2022) was not focused because the idea is not to discuss geoconservation issues, but to use the sites to exemplify environmental impacts related specifically to human activities.

Classification of Geodiversity-Biodiversity Relationships

After the selection and description of geosites, a classification scheme based on the approaches on the type of relationships between abiotic and biotic elements was proposed. This classification is important since relationships between geodiversity and biodiversity are a complex topic and may happen in different scales, contexts and through different mechanisms. Therefore, to enhance the potential educational use, the classification scheme was proposed, so users of the inventory will be able to better understand it and plan their activities according to their learning objectives.

The classification scheme was based on the interactions identified in the geosites evaluated so far. Since it is the first time that such a thematic inventory is proposed, it is important to highlight that new classes may be identified through the identification of new geosites and, especially, with the development of inventories in different morphoclimatic and morphogenetic contexts.

Finally, educational objectives were defined for each class, showing how the geosites can be used to approach different concepts and topics. The objectives were proposed based on the representativeness of the identified types of interactions and their educational potential. Since the thematic inventory is focused on the educational use, to have a clear definition of objectives is a fundamental step.

The classes proposed in the present work are presented in Table 2. The geosites, depending on their characteristics, may represent different types of interactions and, therefore, may be included in more than one class.

Results

Selection and Characterisation of Geosites

There are 19 geosites identified and described so far (Fig. 1). Advances on the research within the geopark territory will allow the identification of more geosites, especially in areas where there is a lack of data. It is possible to observe a concentration of geosites in the southern portion of the area, which can be explained by the presence of the Cabo Frio Centre of Plant Diversity, a vegetational hotspot which has been extensively studied. The northern portion, although presents relevant biological aspects, still needs more studies.

A brief description of each geosite is presented on Table 3, which summarises their main characteristics and relevant aspects concerning the relationships between geodiversity and biodiversity. The table presents simplified information since each geosite has its own descriptive file, as presented in the methodological procedures topic. Table 4 presents an example of a fully described geosite.

Classification of Geodiversity-Biodiversity Interactions

After the selection and characterisation of sites, they were classified according to the type of interactions they represent. Table 5 presents the geosites representing each class.

It is interesting to highlight some geosites, such as *Vermelha* Lagoon and *Maricá* Barrier-Lagoon System are present in many classes, which means that they represent different types of relationships. This characteristic enhances the educational potential of these sites since different topics can be approached in them.

Therefore, the main result of this research was the creation of a model of inventory of geosites representing geodiversity-biodiversity relationships, including two main steps: characterisation and classification. It is intended to be used mainly, but not exclusively, in educational activities, highlighting the importance of considering nature as a system embracing physical and biological elements and strengthening the idea that conservation efforts need to account geodiversity to be successful.

Discussions

Relationships between geodiversity and biodiversity are complex and may happen in different scales and through different mechanisms (see Tukiainen et al. 2022). Understanding these relationships is a challenge with great potential to be used in conservation strategies. Therefore, introducing this topic into educational contexts is essential to bridge the gap between the physical and biological environments that still exist in most nature conservation efforts. The creation of the thematic inventory is intended to be a tool to contribute to this context, strengthening educational initiatives through the use of geosites. More than contributing only to a local context, it is expected that this type of inventory is developed in other areas.

As presented by Brilha and Catana (2020), geoparks are areas in which educational activities are promoted, contributing to both formal and informal education. Geoparks often have partnerships with schools, universities, and other institutions. Geosites are widely used for education in geosciences in several contexts, contributing to the training of undergraduate and graduate students and to the popularisation of geoscientific knowledge to the society. Therefore, introducing the topic of geodiversity-biodiversity relationships in geoparks has the potential to enhance the relevance of the topic.

Table 3 Summary of the main characteristics of each geosite

1. Stone Mangrove	Very rare mangrove developed on a basement composed of gravel and coarse sand. Aquifers on sedimentary rocks provides freshwater for the development of the vegetation.
***2. São João* Hill**	Alkaline intrusion creating a high isolated hill on the coastal plain. The vegetation on the hill has physiognomic differences from those around it and composes an important Atlantic Rainforest remain.
3. *Jurubatiba C*oastal Barriers	Coastal barriers representing past relative sea-levels, higher than at present, with the presence of several coastal lagoons. The environment hosts a highly biodiverse sandbank vegetation, adapted to the local conditions. The area is protected by a National Park.
4. *Peró* Dune Field	Dune field composed of several dune types, hosting endemic fauna and flora species and dune pioneer vegetation. The area is threatened by the construction of a resort, representing high risks for the geodiversity and biodiversity.
5. *Dama Branca* Dune Field	Biggest dune field in SE Brazil, presenting a high diversity of dune types and areas subjected to flooding, creating “natural pools”. It hosts different vegetation types, adapted to the different environments within the dune field, as well as endemic species. The area is impacted by urban growth in the source area of the sediments feeding the dunes.
6. *Cabo Frio* Island	Alkaline intrusion creating an island with high scenic beauty and rich biodiversity, including endemic species, and geodiversity. Part of a protected area where fishermen need to follow rules focused on the conservation of the biodiversity, but maintaining the economic activity, which is traditional in the area. Interesting to address management issues. There is also the *upwelling* phenomena, where cold waters with nutrients are brought to the surface, enhancing the presence of fishes and, consequently, enhancing fishing activities.
7 .*Jacarepiá* Lagoon	The only coastal lagoon with freshwater in the region, which creates specific conditions for fauna and flora, including species in risk of extinction. Subjected to environmental impacts due to urban occupation in its surroundings.
8. *Vermelha* Lagoon	Double barrier-lagoon system where it is possible to observe the type of vegetation occupying each local environment (beach, foredunes, lagoon). Besides that, there are occurrences of holocenic stromatolites due to the high salinity of the main lagoon, which represents a rare geodiversity-biodiversity combination.
9. *Búzios* Palaeolagoons	Lowlands subjected to flooding, which were occupied by lagoons during higher sea-levels in the Holocene. The area has specific vegetation types, adapted to the conditions, and is also important for migratory birds. Subjected to environmental impacts, including drainage for urban occupation and channel construction for boats.
10. *Sapiatiba* Mountain	Coastal massif, among the highest of the region, covered by sub-montane forest, being an “island” among lowlands strongly affected by deforestation. The area allows a clear observation of the relief forms influencing the vegetation types in the region and analysis of the deforestation in the area.
11. *São João* River Mouth	Area of interface between saltwater from the ocean and freshwater from the river, typical environment where mangrove vegetation develops. Interesting to analyse in comparison to the Stone Mangrove, which is an uncommon occurrence.
12. *Salgada* Lagoon	Coastal lagoon located in the delta of *Paraíba do Sul* River, the main river of Rio de Janeiro State. The characteristics of the water, especially its salinity, creates an environment where microorganisms thrive and create stromatolites by removing Ca and CO2 from the water and producing calcium carbonate.
13. *José Gonçalves* Marine Terrace	The terrace was created during moments of higher sea-level during the Holocene. Nowadays, it is almost entirely covered by sandbank vegetation. The area is interesting for being possible to observe the active marine processes at the beach and to see the biological differences in this active portion and in the terrace (inherited landform), an approach on the temporal scale of geodiversity-biodiversity relationships.
14. *Una* Fluvial Plain	The *Una* River is of high regional importance for the biodiversity and for human use, especially irrigation. However, it is being more and more affected by negative impacts, especially sewage dump. The area allows the observation of how human action may affect the river and, consequently, the associated biodiversity.
15. *Iquipari* Lagoon	Coastal lagoon formed by the natural damming of a small river due to marine deposition of sand, creating an ecosystem marked by the presence of a freshwater body close to the ocean. It created conditions for the development of a unique flora, different from the surrounding areas, and with the presence of both salt and freshwater fauna species. The lagoon is also very important for the fishing communities in the region. In the 1990’s, there was an artificial opening of a channel, and the impacts are described in the scientific literature.
16 .*Maricá* Barrier-lagoon System	Partially covered by a Protected Area, it is marked by the presence of a double barrier-lagoon system and wetlands in areas which were covered by lagoons in periods of higher sea-levels in the past. Besides the biodiverse sandbank vegetation in the coastal barrier, the wetlands are recognized as highly relevant for migratory Nearctic birds.
17. *Guaxindiba* Tableland Forest	The most representative tableland forest in Rio de Janeiro State. The tablelands are landforms developed on sedimentary rocks from the Neogene. The mostly flat terrain and the well-developed soils allow the development of Semideciduous Seasonal Forest. It is also known as Coal Forest due to the intense impact of coal production, which destroyed a significant portion of the forest. *Guaxindiba* is now a Protected Area responsible for preserving the most important remain of this vegetation type.
18. *Mato Grosso* Mountain	One of the highest coastal massifs in the region, formed due to tectonic movement during the Cenozoic and composed of rocks related to the *Búzios* Orogeny. The area is interesting for allowing the observation of the effect of altitude in vegetation changes, presenting different physiognomic and compositional types.

Table 3 (continued)

19. ***Pai Vitório*** **Point**	The southern portion of the Geopark is marked by a climatic peculiarity, being a semi-arid enclave. In *Pai Vitório* point, it is possible to clearly see the peculiar vegetation that occurs due to the climatic conditions, including physiognomic adaptations and endemic cacti species.

Table 4 Full description of the Stone Mangrove geosite according to the proposed method

Stone Mangrove	
Localisation	*Gorda* Beach, Armação dos Búzios, RJ; 24 K 195,566 E 748,297 S
Geodiversity	Coastal talus deposit, composed by several types of rocks, at the "foot" of a high declivity hill. Occurrence of sedimentary rocks (*Barreiras Formation*) locally conditioned by a major fault. The rocks host aquifers that send freshwater into the ocean through the underground.
Biodiversity	Uncommon occurrence of mangrove vegetation, completely different from the surrounding. Studies indicate that it is a young occurrence, and it is still undergoing a process of development and consolidation, which makes it more fragile to impacts from human activities.
Geo-Bio relationships	The vegetation is directly conditioned by the freshwater coming from the aquifers present in the sedimentary rocks. There is no influence of rivers. The mangrove thrives on a ground composed of grains varying from coarse sand to boulders (talus deposit), which is unusual since most mangrove vegetation develop on mud and are associated to rivers. Therefore, this geosite represent a rare relationship between geodiversity and biodiversity elements.
Spatial scale	Local occurrence, related to integrated geological, geomorphological and hydrogeological elements that only occur in this part of the beach, close to a coastal hill.
Temporal scale	The vegetation is recent and is still developing since the physical conditions were only established in the late Holocene, after a period of higher sea level around 5 thousand Years BP. It makes the geosite interesting to approach the temporal scale of the relationships and themes related to environmental changes.
Risks and degradation	The area was recently legally protected. However, there are still risks of diminishing of freshwater flow due urban occupation around the Protected Area. The reduced flow can lead to impacts on the vegetation since it depends on the balance between fresh and saltwater to keep developing. This example also shows the complexity related to active process because the impacts come from areas outside the perimeter of the Protected Area.

The inventory presented in this work was designed considering the inherent complexity of geodiversity-biodiversity relationships. In each geosite, different characteristics are highlighted, approaching issues related to spatial and temporal scale, risks and degradation, the mechanisms in which geodiversity influences biodiversity etc.

Table 5 Geosites identified in each class of geodiversity-biodiversity interaction types

Class	Geosites
Natural diversity	• *Dama Branca* Dune Field; • *Vermelha* Lagoon; • *Maricá* Barrier-Lagoon System.
Specific elements	• Stone Mangrove; • *Cabo Frio* Island; • *Jacarepiá* Lagoon; • *Vermelha* Lagoon; • *Salgada* Lagoon; • *Iquipari* Lagoon.
Large-scale relationships	• *São João* Hill; • *Jurubatiba* Coastal Barriers; • *Peró* Dune Field; • *Dama Branca* Dune Field; • *Cabo Frio* Island; • *Búzios* Palaeolagoons; • *Sapiatiba* Mountain; • *São João* River Mouth; • *Guaxindiba* Tableland Forest; • *Mato Grosso* Mountain; • *Pai Vitório* Point.
Temporal relationships	• *Jurubatiba* Coastal Barrier; • *Vermelha* Lagoon; • *Búzios* Palaolagoons; • *José Gonçalves* Marine Terrace; • *Iquipari* Lagoon; • *Maricá* Barrier-Lagoon System; • *Pai Vitório* Point.
Uncommon relationships	• Stone Mangrove; • *Vermelha* Lagoon; • *Salgada* Lagoon.
Environmental impacts	• Stone Mangrove; • *Jacarepiá* Lagoon; • *Búzios* Palaeolagoons; • *Una* Fluvial Plain; • *Iquipari* Lagoon.

An interesting issue to be discussed is the influence of geodiversity itself and the influence of specific abiotic elements in providing conditions for the development of biological elements. At the geosite *Maricá* Barrier-lagoon System (Fig. 2) it is possible to observe how the diversity of geomorphological elements supports the vegetational diversity in the area. The Holocene Barrier (*Barreira Holocênica*) is occupied by Halophilous-psamophilous communities, adapted to the conditions of high salinity and sandy soils. The palaeolagoons (*Planície lagunar*) host herbaceous wetlands due to its seasonal flooding conditions. There are frontal dunes between the barrier and the palaeolagoons that are occupied by scrub vegetation (greener part

Fig. 2 *Maricá* Barrier-lagoon System seen from above (photo: Desirée Guichard, source: Santos et al. (2017). Translation from the terms in Portuguese: *Lagoa de Maricá*– Maricá Lagoon; *Margem lagunar* – Lagoonal margin; *Barreira Pleistocênica* Pleistocene Barrier; *Planície lagunar* – Lagoonal plain (palaeolagoons); *BarreiraHolocênica* – (Holocene Barrier)

Fig. 3 **A** – *Jacarepiá* Lagoon, the only freshwater lagoon in the region (photo: Pedro Arnt; **B** – Stromatolites at *Salgada* Lagoon (photo: Lucas Alfano)

Fig. 4 **A** – Mangrove at *São João* Rivermouth and *São João* Hill at the back. (source: geoparquecostoeselagunas.com.br); **B** – Stone Mangrove and its unusual substrate (photo: Kátia Mansur)

in Fig. 2). Seasonal Dry Forests occur on the Pleistocene Barrier (*Barreira Pleistocênica*) and the lagoonal margin (*Margem Lagunar*) also hosts herbaceous wetlands. Therefore, the geosite has a strong educational potential concerning the different vegetation types in this coastal tropical environment.

Different from the previous example, where the diversity of geomorphological elements is linked to the diversity of vegetation, the geosites of *Jacarepiá* Lagoon (Fig. 3A) and *Salgada* Lagoon (Fig. 3B) presents situations where a specific characteristic (not the diversity of elements) of the physical environment provides conditions for the development of specific biota. *Jacarepiá* Lagoon is the only freshwater lagoon in the region, so there are fauna and flora species that only occur there, and *Salgada* Lagoon has environmental conditions, especially the salinity, that allow the existence of microorganisms that create stromatolytes, which is a rare type of sedimentary rock.

Some geosites represent uncommon relationships between physical and biological elements, being interesting targets for educational activities. At *São João* River Mouth (Fig. 4A) there is a "traditional" occurrence of mangrove, located at the interface of freshwater from the river and saltwater from the ocean. Together with the mud substrate, these are the common conditions for the development of mangrove vegetation. However, at the Stone Mangrove

(Fig. 4B) there is a highly peculiar occurrence of this type of vegetation since there is no river and the substrate is mainly composed of gravel and coarse sand. The comparative analysis between the two geosites allows discussions on how specific vegetation types may develop in "normal" conditions or due to peculiar characteristics of the physical environment, an example on how complex relationships between geodiversity and biodiversity may be.

Concerning the temporal scale of the relationships, *Iquipari* Lagoon (Fig. 5A) shows an interesting example on how recent geomorphological processes may create conditions for the setting of specific biota. The natural damming of a river by deposition of sand due to marine processes was responsible for alterations on the local characteristics of the water and, consequently, for the setting of a specific biota, different from the surrounding areas. This relationship is recent and the inherent characteristics of the geosite makes it fragile. Evidence of such fragility is described by Suzuki et al. (2002), which described the consequences of a temporary artificial opening of the sand bar that led to significant environmental changes, affecting the water and the local biota.

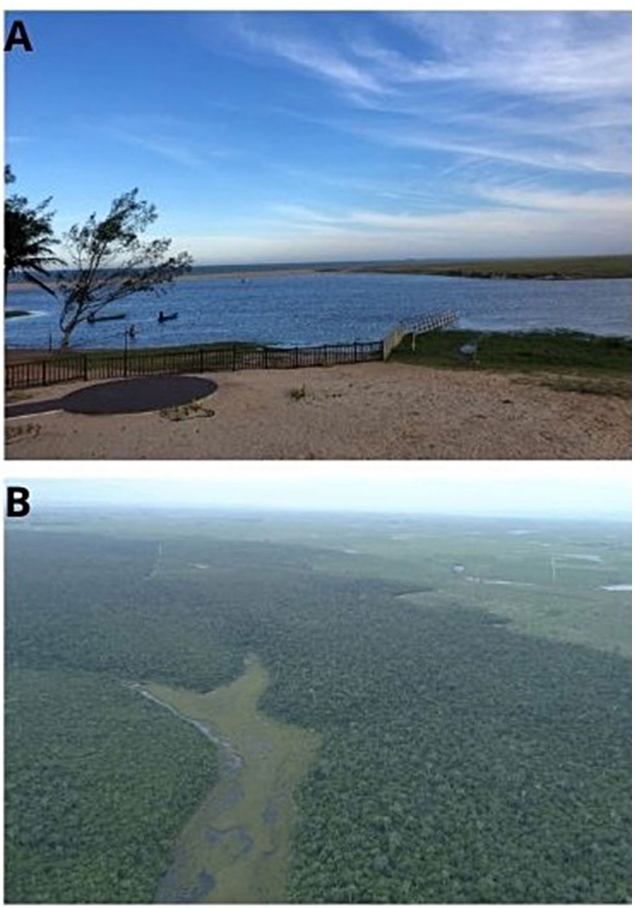

Fig. 5 **A** – *Iquipari* Lagoon. In the back, it is possible to observe the short distance to the ocean (photo: Kátia Mansur); **B** – *Guaxindiba* Tableland Forest and its flat geomorphological setting (photo: Kátia Mansur)

At *Guaxindiba* Tableland Forest (Fig. 5B), on the other hand, the geological/geomorphological conditions are more stable through time. The tableland forest is older and the fragility to environmental changes is lower. The previous two examples may be used to discuss issues related to the stability and enduring characteristics of geofeatures. As discussed by Tukiainen et al. (2022), although not all geofeatures are stable, they can still be used as surrogates to conserve species, especially when considering the current global environmental changes.

The geosite *José Gonçalves* Marine Terrace (Fig. 6A) is also interesting for approaches on the temporal scale of geodiversity-biodiversity relationships. The terrace was built by sand deposition during a period of higher sea-level in the Holocene, being an inactive landform nowadays. The beach located right in front of the terrace shows the active marine processes creating a balance between sand deposition and erosion. These two environments are spatially connected, but "timely separated" and the biota is completely different in each of them. The terrace is occupied by sandbank vegetation and the beach has specific fauna species, with no vegetation due to the direct influence of the ocean.

The spatial scale is a relevant aspect to be considered since some geofeatures of great proportions have strong influence in the setting of biological elements. An example can be seen in *Jurubatiba* Coastal Barriers (Fig. 6B), where the specific geomorphological setting of aligned coastal barriers and presence of several coastal lagoons is responsible for a high biodiversity. The importance of the natural diversity is such that a national park was created to protect the area. More information about this site can be found in the E-Book *Parque Nacional da Restinga de Jurubatiba: Geodiversidade Protegida* (Restinga de Jurubatiba National Park: Protected Geodiversity), available in Portuguese and English and free to download in the geopark website (https://www.geoparquecostoeselagunas.com/parque-nacional-da-restinga-de-jurubatiba/ - Access on 17th April, 2023).

Another issue that can be discussed based on the inventory is the occurrence of environmental impacts affecting the geodiversity and, consequently, the biodiversity of an area. At *Búzios* Palaeolagoons, a flat area subjected to flooding (Fig. 7A) and marked by the presence of water bodies with high relevance for the avifauna, real estate development is being responsible for drainage in some areas and for the construction of artificial channels connecting these water bodies to the ocean in others (Fig. 7B). This process is leading to severe consequences to the environment, affecting both flora and fauna.

The geosite *Dama Branca* Dune Field (Fig. 8) presents an interesting and concerning environmental impact related

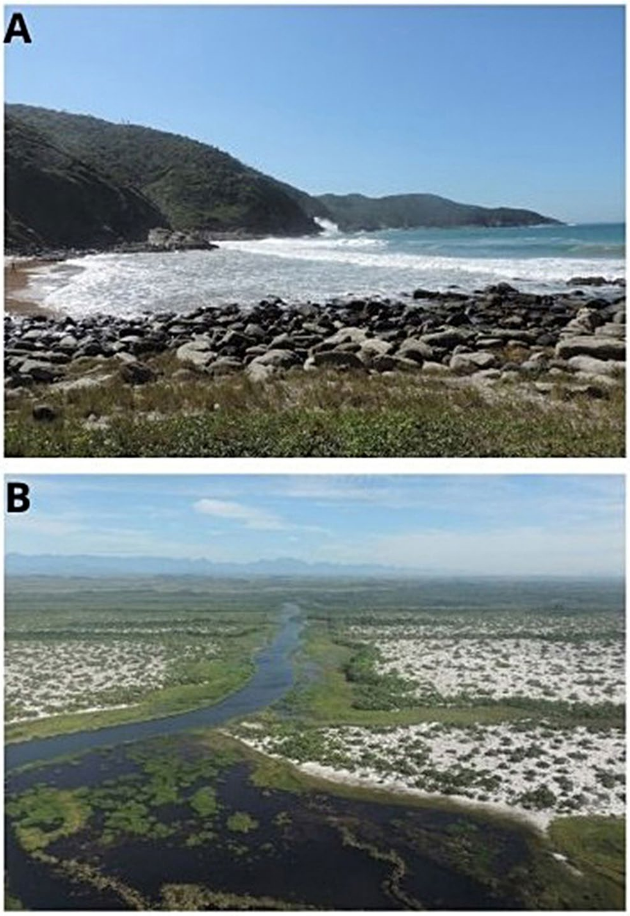

Fig. 6 **A** – José Gonçalves Beach. The actual beach is associated with boulders and a holocenic marine terrace, located above the current sea level; **B** – Coastal barriers and lagoons at *Jurubatiba* National Park (photos: Kátia Mansur)

Fig. 7 **A** – *Búzios* Palaeolagoons and its flat areas; **B** – Construction of channels to connect the area to the ocean (photos: Daniel Santos)

Fig. 8 *Dama Branca* Dune Field seen from a satellite image. It is possible to observe the advance of urban occupation in its surroundings, especially at the beach, which is the main source of sediments feeding the dunes. (source: Google Sattelite, QuickMap Services – Qgis)

to urban growth. The dunes are fed by sediments from the beach nearby, where the finer sediments are carried by the wind. The urban occupation of the area is affecting this transport and, since the main dunes in the area are active landforms, this process may lead to severe modifications in the environment. This case has educational interest for showing the complexity related to active process. The driver of the impact is not on the site itself, however, the effects of it are affecting the dune field and, therefore, affecting the biota living there.

All the geosites in the inventory can be used to approach the idea of ecological support role (Panizza 2001; Bollati et al. 2015) since in every situation, independent of the peculiarities of each site, it is possible to observe how the physical setting influences the development of biological elements. Also, the sites representing environmental impacts are interesting for approaches on the CNS concept for their representativeness of impacts in the physical environment and the consequences for the biodiversity, highlighting the need for integrated efforts for nature conservation.

Concerning the definition of educational objectives, although this is a fundamental step, it is worth noting that users of the inventory may identify other possible objectives. The ones proposed here are more a guideline than a rule. However, regardless of that, it is important to stress that having educational objectives enhances the potential use of the inventory by helping in the planning and organisation of activities.

Fig. 9 Photo of the event *Geodia* (Geoday) at *Salgada* Lagoon, that happened on 15th April 2023. The event, promoted by the geopark, consists of educational visits to geosites with the community to discuss their relevance, need for protection and to celebrate the geodiversity (photo: geoparquecostoeselagunas.com.br)

Education is one of the fundamental aspects sustaining geoparks. They offer opportunities to develop a series of activities with potential to enhance geoscience and environmental education. Catana and Brilha (2020) highlight the role of geoparks in promoting the United Nations Sustainable Goals and the presented inventory, by focusing on an integrated analysis of nature, including impacts of human activities, can also contribute to this issue. Quality Education and Life on Land were identified as the main ones. However, considering that the inventory may be used for geotourism in an area where tourism is one of the main sources of income, Decent Work and Economic Growth, and Reduced Inequalities are also goals that could be positively affected using the inventory. Since geotourism and educational activities are already taking place through the geopark, the strengthening of the geodiversity-biodiversity topic opens new possibilities.

The proposed inventory is not restricted to the geologic/morphoclimatic context of the Geopark *Costões e Lagunas*. There are published works dealing with geodiversity-biodiversity relationships in many different contexts (e.g. Sassa and Yang 2019; Toivanen et al. 2019; De Falco et al. 2021; Bollati et al. 2023) and the method for characterisation and classification of geosites proposed is expected to be appliable to any of them, since no specific condition of the study area was considered in the development of the method. Based on that, the development of this type of inventory in different contexts would be interesting to test and, eventually, propose modifications in order to improve the method, even including new classes of interaction.

Conclusions

Educational activities are a fundamental part of Geoparks, which are areas where geoeducation is valued and promoted to the society through different initiatives. The topic of relationships between geodiversity and biodiversity is relatively new and efforts to make it more present in educational contexts, both formal and informal, contribute to the process of consolidation of integrated studies of nature that take into account the complexity of the natural environment and the human action on it. The thematic inventory presented here is an effort in this direction.

The Geopark Cliffs and Lagoons project have been developing many educational and geotouristic activities (Fig. 9). The geodiversity of the area allows approaches on different topics within the geosciences. The creation of the presented inventory was an attempt to explore this specific topic that has been growing in importance in the last years. Similar initiatives may take place in other areas as well, so the benefits provided will not be restricted to the area of the Geopark. We hope this manuscript becomes an incentive to that.

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