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Article

Qualitative Map of Geodiversity as a Tool to Identify Geodiversity-Related Ecosystem Services: Application to the *Costões e Lagunas* Aspiring Geopark, SE Brazil

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Abstract

Geodiversity mapping is a key topic in the field of geoconservation. Although most methodological proposals are based on quantitative assessments, recent studies on qualitative mapping have shown strong potential for various applications, including relationships with biodiversity, territorial management, and nature conservation. This article presents a qualitative geodiversity map of the *Costões e Lagunas* Aspiring Geopark, located in the state of Rio de Janeiro, Brazil. The map was also used to identify geodiversity-related ecosystem services in the territory. The method for generating the map was divided into two steps: first, thematic maps representing geodiversity components were integrated to identify areas where components interact to form specific environments; second, based on these interactions, geodiversity units were defined. Ecosystem services provided by each unit were identified through the analysis of human activities occurring within them. The results show that the geodiversity units provide multiple ecosystem services across different categories and are essential to the well-being of local inhabitants. These findings reinforce the relevance of the qualitative approach and demonstrate that geodiversity mapping can support broader landscape analyses. Thus, qualitative geodiversity maps are effective tools for identifying ecosystem services across extensive areas.

Keywords: geoconservation; geodiversity assessment; physical environment; abiotic environment

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1. Introduction

Geodiversity, which corresponds to the variety of geological, geomorphological, pedological, and hydrological elements and processes, is a concept that has become a fundamental topic within contexts such as territorial management and nature conservation. Among the various applications of this concept, several studies are exploring its importance for the assessment of ecosystem services (e.g., [1–5]).

The term *geosystem services* have been used to emphasize the relevance of geodiversity within the context of ecosystem services. Ref. [6] acknowledges that, although the concept of an ecosystem includes the abiotic environment, most of the published works on ecosystem services were focused on the biotic environment, without recognizing the importance of geodiversity.

Refs. [6,7] used the results of the Millennium Ecosystem Assessment [8] to propose a classification for the services provided by geodiversity, which were called *geosystem services* or *abiotic ecosystem services*. As an innovative and widely accepted proposal, the Millennium Ecosystem Assessment classified the services provided by nature into four categories: provisioning, regulating, cultural, and supporting. Refs. [6,7] present his classification based on values (intrinsic, cultural, aesthetic, economic, functional, and scientific/educational) and divides the *geosystem services* into provisioning, regulating, cultural, supporting, and knowledge. Ref. [1] later considered the knowledge services as a subcategory of the cultural services.

A problem was highlighted by [9]: the unclear position of geodiversity within ecosystem services frameworks. In response, they proposed the Geo-Eco Services Framework, designed to recognize not only services related solely to geodiversity but also those arising from the interactions between biotic and abiotic elements and processes. Within this framework, the services provided exclusively by geodiversity are termed *geosystem services*. The services resulting from interactions between biodiversity and geodiversity are further divided into *geodiversity-driven* and *biologically driven* ecosystem services, depending on the elements and processes primarily driving the provision of these services.

In a comprehensive review, Ref. [10] analyzed multiple approaches on the services provided by biotic and abiotic nature, concluding that few studies worldwide are dedicated to the services provided by geodiversity when compared to those dealing with biodiversity. However, they emphasize the importance of integrating the analysis, given the need to evaluate ecosystems in their various aspects.

Qualitative geodiversity maps (e.g., [11,12]) are valuable tools for land-use planning, as they reflect the physical structure of the territory and inform potential uses and limitations. Their integration with ecosystem service assessments can enhance territorial management strategies. In coastal regions, however, this approach should also incorporate the identification of threats such as sea-level rise due to climate change, and coastal erosion, which could lead to the possible loss of areas where the ecosystem services provided are of high natural and social relevance, or even important geosites.

This article aims to present the qualitative map of geodiversity of the *Costões e Lagunas* Aspiring Geopark (GpCL), located in the state of Rio de Janeiro, Brazil. The map was used to identify ecosystem services provided by geodiversity elements, as well as to interpret potential climate-related threats to these environments.

In geopark territories, which must deal with the various dimensions of heritage, whether natural, built, material, or immaterial, the need to evaluate the territory as a whole becomes evident, taking into account the pillars for its certification by UNESCO, (i.e., people, landscape, geological heritage, geoconservation, geotourism, and sustainable local development). Therefore, an assessment of ecosystem services becomes a valuable tool for conducting an integrated analysis of both natural and social aspects. In the case of the GpCL, there is also another important factor to be considered, which is its location in a coastal area subject to relative sea-level rise and coastal erosion due to climate change [13] and an increase in the number of extreme events in the forms of storm waves and intense rainfall.

The results presented in this article were obtained through the execution of the project "Analyzing the past to think about the future: variations in relative sea level in the territory of the *Costões e Lagunas* Geopark in Rio de Janeiro" (in Portuguese: *Análise do Passado para pensar o futuro: as variações do nível relativo do mar no território de Geoparque Costões e Lagunas do Rio de Janeiro*), supported by the National Council for Scientific and Technological Development—CNPq (Brazilian Government).

2. Study Area

The study area is the territory of the GpCL, which encompasses 16 coastal municipalities in Rio de Janeiro State, SE Brazil (Figure 1).

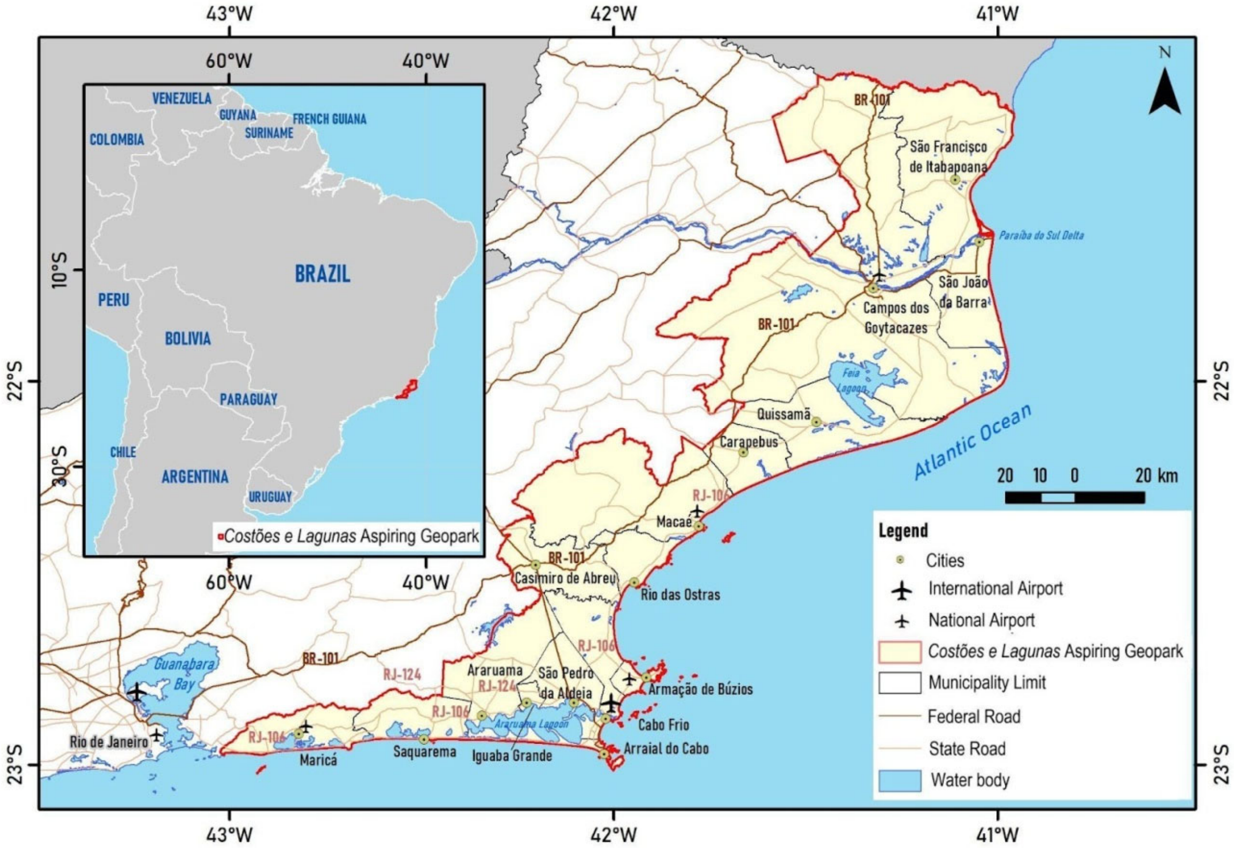

Figure 1. Location of the *Costões e Lagunas* Aspiring Geopark (modified from www.geoparquecostoeselagunas.com).

The territory has a rich geodiversity [14,15] represented in terms of geology, geomorphology, soils, and hydrography. Its territorial dimension of around 11,000 km^2 encompasses vast areas of freshwater to hypersaline lagoons, wetlands, mountain ranges, hills, dunes, cliffs, islands, beach ridges, coastal barriers, and rocky coasts, which are home to a rich biodiversity and endemism of fauna and flora [16], as well as a differentiated climate, from semi-arid to humid tropical [17].

The geology of the area spans some 2 billion years of evolution. It has records dating back to the Paleoproterozoic, represented by the occurrence of African rocks associated with the Angola Craton in Brazilian territory [18]. It is considered important evidence of continental drift. It also includes rocks that represent the collision of the Gondwana Supercontinent, from the Neoproterozoic to the Cambro-Ordovician, including ophiolites, pegmatites, and granites [19–23] and their respective break-up in the Cretaceous [24].

The region's basement rocks, which extend into the marine area adjacent to the GpCL territory, also mark the boundary between Brazil's two most productive oil and gas basins, the *Campos* and *Santos* sedimentary basins [25–27].

After a period of tectonic quiescence, it recorded an event of intraplate alkaline magmatism at the Mesozoic–Cenozoic boundary [28–32] and sedimentation and tectonism in the Neogene, in the form of continental deposits and a significant fault system [33–35].

This evolution continued until the Quaternary sedimentation of its vast coastal plain, from the Upper Pleistocene onwards, with local deposition of aeolian dunes and the formation of a series of lagoons, some of which are characterized by the construction of Holocene stromatolites [36–46].

From a geomorphological perspective, the territory of the GpCL is characterized by high diversity, including Quaternary coastal and continental features, alkaline massifs related to Mesozoic–Cenozoic magmatism, and coastal massifs and mountain ranges formed by rifting processes associated with the opening of the Atlantic Ocean. Anthropogenic landforms are also worthy of consideration.

During the Quaternary, sea-level variations were responsible for the formation of coastal lagoons and sand barriers of different ages. The most recent drop in relative sea level during the Holocene led to the reduction of some lagoons, resulting in swampy areas occupying paleolagoons [47–49]. The semi-arid climate of part of the territory contributed to the development of the largest dune fields in southeastern Brazil, including the *Dama Branca* geomorphosite, which is included in the inventory presented by [50].

Outcrops of sedimentary rocks from the *Barreiras* Formation (Neogene) sustain tablelands, particularly in the northern portion of the territory [33]. This formation is also responsible for the occurrence of cliffs and paleocliffs, which indicate higher sea levels in the past [50].

The Mesozoic–Cenozoic is marked by tectonic and magmatic events that were responsible for the development of coastal massifs and mountain ranges. The alkaline magmatism [28] is represented in the territory by two sites, *São João* Hill and *Cabo Frio* Island, both of which are prominent in the landscape due to their altitudes. Other coastal massifs and the mountain ranges present in the inner portions of the territory originated from rifting processes that took place between the Upper Jurassic and Lower Cretaceous, associated with the opening of the Atlantic Ocean [51].

Anthropogenic deposits are almost exclusively more prominent in urban areas. However, in the GpCL territory, vast anthropogenic landforms, originated from *salinas* and established since the 19th century [52,53], occupy the surroundings of Araruama Lagoon and the small lagoons of the Holocene sand ridges.

The geological and geomorphological diversities are associated with high soil diversity. A total of 17 soil sub-orders can be found in the territory [54], occurring in several types of environments. Carbic Spodosols occur in the marine terraces; haplic, organic, and sulfidic gleysols occur in the paleolagoons and fluvial environments, which also host fluvic neosols and hydromorphic planosols; and ultisols and oxisols occur in the coastal massifs, low hills, and in parts of the mountainous regions, while inceptisols occur in the highest and steeper areas of them. Finally, histosols occur in some specific environments influenced by water, such as fluvial plains and coastal lagoons.

The GpCL territory is rich in water bodies, ranging from hypersaline to freshwater. These include high-flow rivers such as the *Paraíba do Sul*, *Macaé*, *São João*, and *Itabapoana*. The area is covered by hypersaline, brackish, and freshwater lagoons, such as those found in the *Araruama* lagoon system; in the *Maricá* and *Saquarema* lagoons; in *Jacarepiá*; and throughout the *Restinga de Jurubatiba* National Park system. In hydrogeological terms, the *Emborê* Aquifer [55] stands out for supplying many cities in the northern area of the territory. It is the most productive aquifer in the state of Rio de Janeiro and is located beneath the river and marine plain in the *Paraíba do Sul* River delta area. Another highlight is the small *Mangue de Pedra* Aquifer [35], which is significant due to its role in sustaining a rare ecosystem.

It is worth mentioning the upwelling of cold waters from the *Malvinas* Current on the southeastern coast of the territory, more precisely around *Cabo Frio* Island, which is responsible for interfering with the semi-arid climate; for the richness of nutrients in the waters, which generates high fish populations; for the hypersalinity in lagoons; for the presence of dune fields; and for the formation of soils that are different from those in adjacent areas with a humid tropical climate.

3. Materials and Methods

3.1. Geodiversity Mapping

The map was developed by adapting the method presented by [11], which is based on the methodology developed by the Geological Survey of Brazil (SGB). The purpose of this qualitative geodiversity mapping is to identify units based on the integration of geodiversity components, according to the definition by [7], namely the geology, geomorphology, soils, and hydrology.

The first step was acquiring maps representing each component (Figure 2). The following maps were used: the Geological Map, scale 1:100,000 [56]; the Geomorphological Map, provided by the Geological Survey of Brazil (SBG) [57], with an original scale of 1:25,000, generalized to 1:100,000 for this study; the Soils Map, with a scale of 1:250,000 [54]; and the Hydrological Map, with a scale of 1:25,000, created by integrating the drainage network and water bodies maps, both provided by the Brazilian Institute of Geography and Statistics (IBGE) [58].

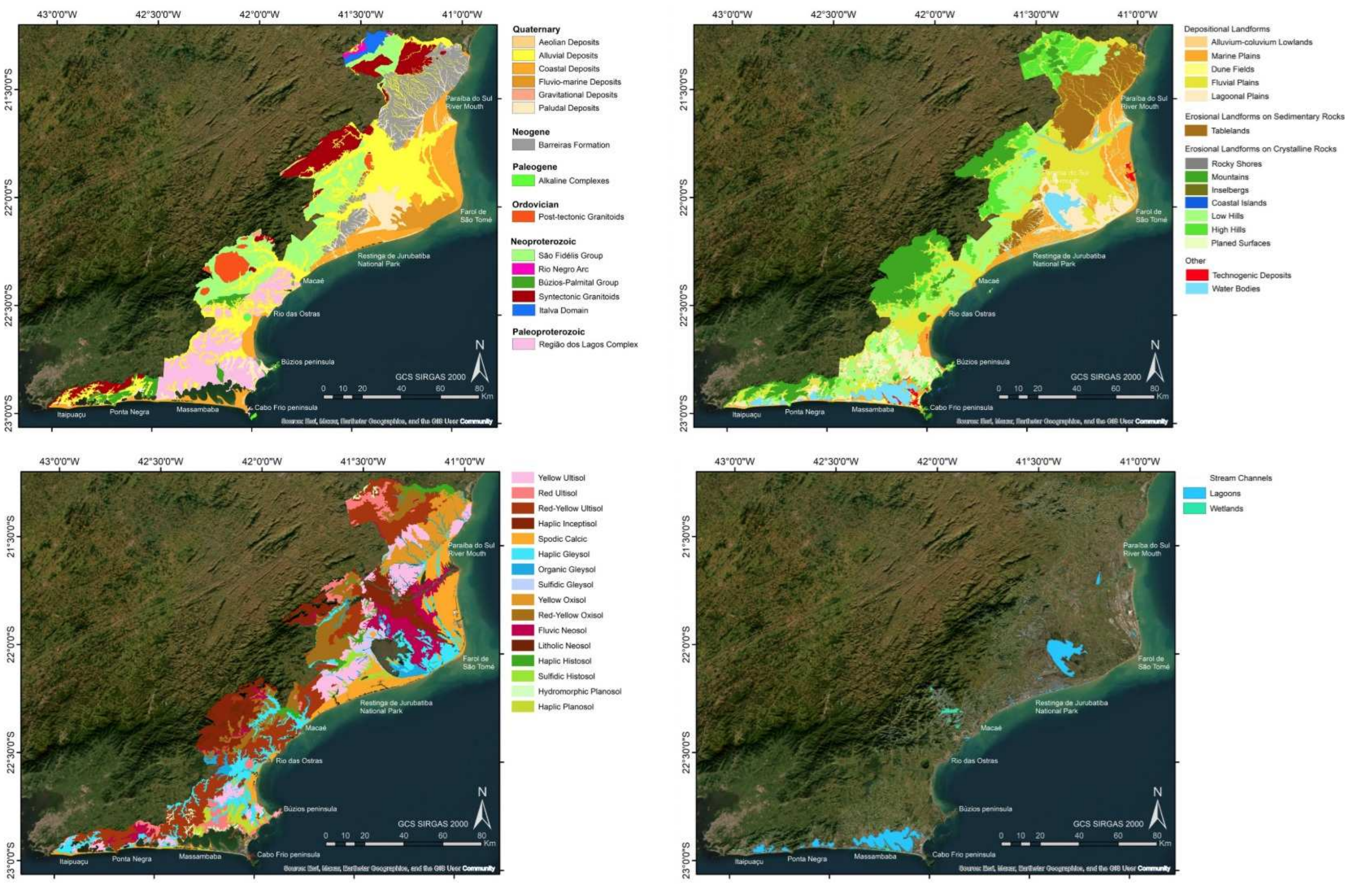

Figure 2. Thematic maps used to create the geodiversity map.

After acquiring the maps, they were integrated using geoprocessing techniques to identify correlation patterns among them. This was done by overlaying the maps using the *Union* tool in the ArcMap software (version 10.6.1). By doing so, it was possible to identify the main associations between geological, geomorphological, and pedological information. No clear pattern was identified between the hydrological information and the other components.

Fieldwork data were then used to refine the identified correlations and to detect patterns that were not evident in the geoprocessing step. By analyzing how geodiversity components influence each other, the units were defined and characterized, highlighting the information that makes them unique. Finally, the geodiversity units were delineated with the aid of the thematic maps, and the qualitative geodiversity map was created.

3.2. Geodiversity-Related Ecosystem Services Identification

This research is based on the Geo-Eco Services Framework described by [9], focusing on the identification of geosystem services and geodiversity-driven ecosystem services, which are referred to here as geodiversity-related ecosystem services. Therefore, biologically driven ecosystem services were not evaluated, as the focus was on using the geodiversity map as the primary source of information.

The classification of services followed the framework presented by [1], which is based on the Millennium Ecosystem Assessment [8] and divides the services into four categories: regulating, supporting, provisioning, and cultural. Although the terminology "geosystem services" and "geodiversity-driven ecosystem services" is not explicitly used by [1], it was considered appropriate for the present research.

Ecosystem services were identified based on the geodiversity units represented on the map. By analyzing the different types of human activities occurring within each unit (e.g., agriculture, tourism, salt production, mining, and scientific research), it was possible to determine the corresponding services and, consequently, the significance of geodiversity elements in the area. The results were organized in a table, associating the geodiversity-related ecosystem services, as defined by [1], with the geodiversity units.

Considering the threats related to sea-level variations that may occur due to global climate change, special focus was given to services that are relevant to the protection of different environments and also to services that may be affected by this process, which included the existence of threatened geosites.

4. Results

4.1. Qualitative Geodiversity Map

The main result of this research is the Qualitative Map of Geodiversity of the *Costões Lagunas* Aspiring Geopark (Figure 3), which was built through the integration of the elements that compose the geodiversity of an area. Each geodiversity unit has its geodiversity-related ecosystem services, composing a tool that can be directly applied to the territorial management of the area.

4.2. Geodiversity Units

4.2.1. Technogenic Units

Technogenic Units are landscape elements created by human intervention. In the case of the study area, it is mostly represented by the *salinas* (Figure 4A), which are areas historically used to produce salt. This activity, which takes advantage of the environmental conditions, occurs around the lagoons with high salinity. They are responsible for alterations in the landscape, originating flat areas that become dry when the activity ceases (Figure 4B). These areas are now targets of urban growth, since the morphology of the terrain facilitates construction. This has been provoking severe environmental impacts in some areas.

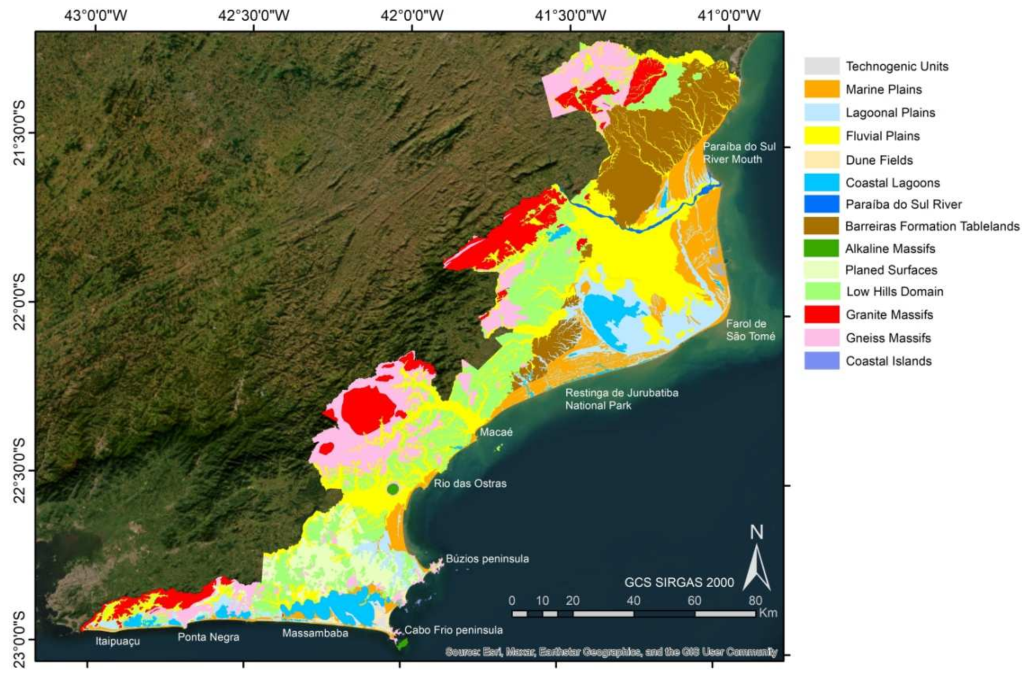

Figure 3. Qualitative Map of Geodiversity of the *Costões e Lagunas* Aspiring Geopark.

Figure 4. (**A**) Active *salina* (photo: Kátia Mansur); (**B**) inactive *salinas* area (source: Google Earth); (**C**) beach ridges (photo: Kátia Mansur); (**D**) barrier–lagoon system (photo: Kátia Mansur); (**E**) wetlands in paleolagoonal area (source: *Costões e Lagunas* Geopark archive); (**F**) Fluvial Plains (source: *Costões e Lagunas* Geopark website—geoparquecostoeselagunas.com, accessed on 30 August 2025).

4.2.2. Marine Plains

The Marine Plains are marine sand deposits forming beach ridges (Figure 4C) or lagoon–barrier systems (Figure 4D). The unit developed during the Quaternary and is strongly influenced by the relative sea-level fluctuations that took place during this geological period. Carbic Spodosols occur in most of the unit, except the beaches that are active and highly dynamic landforms due to the influence of the ocean. These are areas with ecological relevance for hosting a highly biodiverse vegetation of *Restinga* (term used to describe the vegetation on coastal sandy areas). This relevant geodiversity–biodiversity relationship was the reason for the creation of protected areas such as the *Restinga de Jurubatiba* National Park and the *Costa do Sol* State Park.

4.2.3. Lagoonal Plains

Lagoonal Plains are areas that, in the past (in moments of higher sea level), were occupied by coastal lagoons, so they are composed of lagoon bottom sediments. Nowadays, these areas are characterized as flatlands highly subjected to flooding (Figure 4E). Some areas are permanently flooded, creating wetlands. Due to this, most of the unit is occupied by gleysols, and the area presents a high ecological relevance due to the vegetation, unique in the region, and also due to the avifauna of this type of environment, including migratory birds.

4.2.4. Fluvial Plains

The Fluvial Plains are associated with the major rivers of the region, especially the *Paraíba do Sul* River, the biggest in the state of Rio de Janeiro, and the *São João* River. Fluvial geomorphological processes are responsible for the deposition of alluvial sediments, creating vast flatlands divided into fluvial terraces and floodplains (Figure 4F). There are two main types of soil in the area, fluvic neosols and gleysols, and the unit is partially subject to flooding, with higher risks on floodplains and lower risks on fluvial terraces.

4.2.5. Dune Fields

Dune fields are aeolian sand deposits that occur close to the coastline. The territory of the geopark is characterized by a variety of dune types, including foredunes, barchans, barchanoids, parabolic, nebkhas, and a parabolic megaform known as *Dama Branca* (Figure 5A), which is the biggest dune in southeast Brazil and one of the most important geomorphosites in the region.

Figure 5. (**A**) *Dama Branca* Dune Field (source: INEPAC); (**B**) sunset at *Maricá* Lagoon (photo: Kátia Mansur); (**C**) traditional fishing community in *Paraíba do Sul* River (photo: Daniel Santos); (**D**) active cliffs (photo: Kátia Mansur); (**E**) *São João* Hill (photo: Kátia Mansur); (**F**) *Cabo Frio* Island (photo: Kátia Mansur).

4.2.6. Coastal Lagoons

The entire territory is marked by the presence of coastal lagoons, justifying the name of the geopark—*Costões* (cliffs) and *Lagunas* (lagoons). The lagoons have different ages, with the major ones, such as *Maricá* (Figure 5B), *Saquarema*, *Araruama*, and *Jacarepiá*, being formed in the Pleistocene, and smaller ones, usually located closer to the ocean, being formed in the Holocene.

An important peculiarity of the lagoons in the region is that some of them are hypersaline and present favorable conditions for the development of rare Holocene stromatolites. At *Brejo do Espinho*, one of the Holocene lagoons, a very rare geological process takes place: the precipitation of dolomites due to the activity of microorganisms [45]. Therefore, the coastal lagoons are a unit of great scientific relevance.

4.2.7. *Paraíba do Sul* River

The *Paraíba do Sul* River is a major river in southeastern Brazil, being of high importance for passing through the territory of the three richest states of Brazil (*São Paulo*, *Rio de Janeiro*, and *Minas Gerais*). The delta formed by this river is of high geoscientific importance for representing records of sea-level variations during the Holocene [59,60] and also evidence of migration of the river mouth from south to north.

The river itself presents ecological relevance with the occurrence of mangrove and other vegetational communities in its borders and islands, as well as social significance due to the existence of traditional fishing communities (Figure 5C). Interventions along the river are responsible for the processes of salinization and erosion in the delta area. As the river flow gets weaker due to dams and water deviation, salt water from the ocean advances towards the continent, which is affecting both biodiversity and human use of water. In addition, sediment supply is reduced by sand mining along the river course, and this, combined with the reduced hydraulic force of the river, makes waves more effective in eroding the delta area, leading to the loss of urban infrastructure. The village of *Atafona*, located at the mouth of the *Paraíba do Sul* River, is one of two Brazilian locations cited as threatened in [13].

4.2.8. Barreiras Formation Tablelands

This unit is conditioned by the existence of Neogene sedimentary rocks that compose the *Barreiras* Formation, which stretches for more than 4000 km along the Brazilian coast. According to [33], in Rio de Janeiro State, this formation is characterized by a variation of mudstones, sandstones, and conglomerates, mostly related to continental and coastal environments.

Geomorphologically, these rocks are related to coastal tablelands and cliffs originated by marine erosion (Figure 5D), differing from the coastal massifs supported by crystalline rocks, where there is no occurrence of cliffs. Oxisols predominate in the area, as previously mentioned in [54], and, especially in the northern portion of the territory, there is strong agricultural use, with the production of sugarcane and fruits such as pineapple and passion fruit.

4.2.9. Alkaline Massifs

The Alkaline Massifs refer to two occurrences, *São João* Hill and *Cabo Frio* Island (Figures 5E and 5F, respectively), which are both geomorphosites present in the inventory of [50]. They are massifs composed of alkaline rocks originated from the Cenozoic magmatic event which originated the *Poços de Caldas-Cabo Frio Alignment*. This geological feature consists of a series of alkaline massifs that stretches for more than 480 km and has its origins in the movement of the South-American Tectonic Plate over a hotspot between the Upper Cretaceous and the Eocene [28].

Both occurrences are isolated steep hills, being among the highest coastal massifs in the region, and are mostly occupied by well-preserved Atlantic Rainforest vegetation. The soil types differ in each massif, with inceptisols occurring in *Cabo Frio* Island and red ultisols in *São João* Hill.

4.2.10. Low Hills Domain

The low hills (Figure 6A) are characterized by rounded relief forms with a low altitude and declivity. Their origin is the erosion that has occurred for millions of years, since the area became more tectonically stable. This process affects the basement rocks, mostly composed of ortho and paragneisses. The predominant soil types in this unit are red ultisols and yellow ultisols.

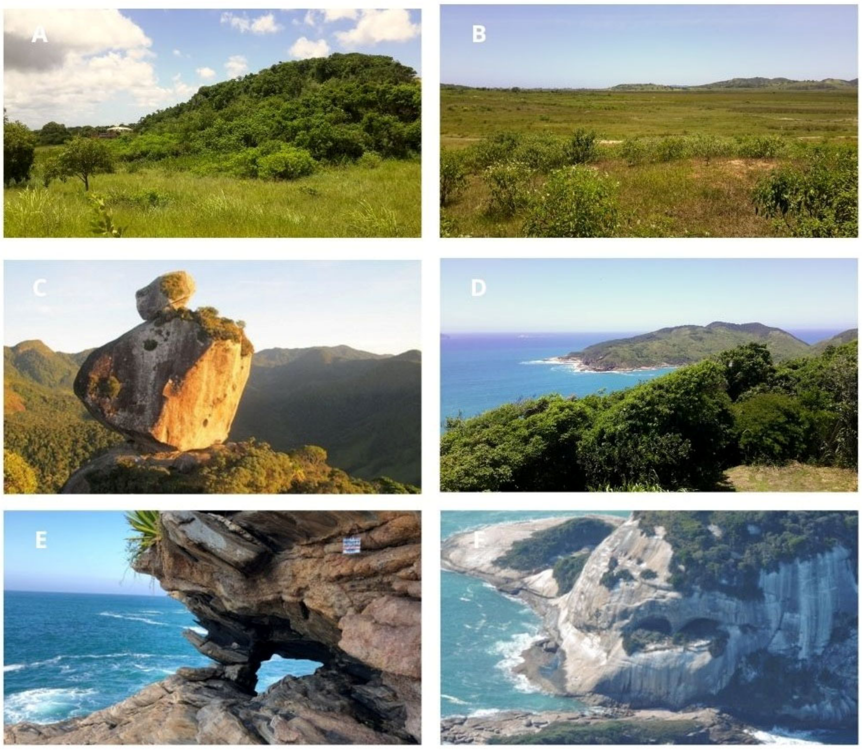

Figure 6. (**A**) Low hills domain (photo: Daniel Santos); (**B**) planed surface (photo: Daniel Santos); (**C**) *Peito de Pombo* Peak (source: *Costões e Lagunas* Geopark website—geoparquecostoeselagunas.com); (**D**) gneiss coastal massifs (photo: Daniel Santos); (**E**) *Sacristia* Cave (photo: Kátia Mansur); (**F**) *Santana* Archipelago (photo: Kátia Mansur).

4.2.11. Planed Surfaces

This unit is also related to the highly eroded areas over basement rocks. The characteristics that mostly differentiate this unit from the low hills domain is the flat topography (Figure 6B), with low declivities, and the occurrence of planosols, which does not happen in any other unit of the study area.

4.2.12. Granite Massifs

The granite massifs are mainly present in the mountainous region, being related to some iconic peaks, such as *Frade* Peak and *Peito de Pombo* Peak (Figure 6C). The granites were formed during the orogenic events that took place during the assembly of the Gondwana, around 600 million years ago. Nowadays, these rocks are characterized by fractures in which the water incision creates waterfalls, such as the ones in *Sana* Village.

4.2.13. Gneiss Massifs

The gneiss massifs occur associated with the granite massifs, being related to the same orogenic events. However, there are also several occurrences of coastal massifs, lower than the inner mountains, which are sustained by gneissic rocks, especially in the southern portion of the territory. Examples of such massifs can be seen in *Ponta Negra* Promontory and in *Armação dos Búzios* Peninsula (Figure 6D). The coastal gneiss massifs eventually present small caves formed by wave action. An example is the *Sacristia* Cave (Figure 6E), an important geosite located in the *Ponta Negra* Promontory.

4.2.14. Coastal Islands

Coastal islands occur throughout the territory and, mostly, have small dimensions. They are composed of the same rocks as the coastal massifs and are related to the same uplift event that occurred in the Cenozoic. These islands are of great ecological relevance, hosting a high variety of fauna and flora species. Some examples of these islands are the *Maricá* Islands and the *Santana* Archipelago (Figure 6F).

4.3. Geodiversity-Related Ecosystem Services

The geodiversity-related ecosystem services are displayed in Tables 1–4, which, by using the categorization of [1], presents the services provided in each unit of the qualitative geodiversity map.

Table 1 presents the provisioning services. It is possible to observe that "food and drink" and "construction materials" are services provided by several units, while the other services are provided by one or two units. Mineral water, industrial minerals (rutile, monazite, ilmenite, and zircon), ornamental rocks, salt, peat, gravel, and sand for civil construction are examples of mineral resources that occur in the territory.

Table 1. Provisioning services in each geodiversity unit.

		Technogenic Units	**Marine Plains**	**Lagoonal Plains**	**Fluvial Plains**	**Dune Fields**	**Coastal Lagoons**	***Paraíba do Sul* River**	***Barreiras* Fm. Tablelands**	**Alkaline Massifs**	**Low Hills Domain**	**Planed Surfaces**	**Granite Massifs**	**Gneiss Massifs**	**Coastal Islands**
Provisioning	Food and drink			■	■		■	■	■	■					
	Nutrients and minerals	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	Fuel			■											
	Construction materials		■	■					■	■	■	■	■	■	■
	Industrial minerals		■						■						
	Ornamental products												■	■	
	Fossils		■	■											

Table 2. Regulating services in each geodiversity unit.

		Technogenic Units	Marine Plains	Lagoonal Plains	Fluvial Plains	Dune Fields	Coastal Lagoons	*Paraíba do Sul* River	*Barreiras* Fm. Tablelands	Alkaline Massifs	Low Hills Domain	Planed Surfaces	Granite Massifs	Gneiss Massifs	Coastal Islands
Regulating	Atmospheric and oceanic processes		X	X		X	X			X			X	X	X
	Terrestrial processes		X	X			X		X		X	X			
	Flood regulation		X	X	X	X	X		X						
	Water quality regulation			X	X		X	X	X						

Table 3. Supporting services in each geodiversity unit.

		Technogenic Units	Marine Plains	Lagoonal Plains	Fluvial Plains	Dune Fields	Coastal Lagoons	*Paraíba do Sul* River	*Barreiras* Fm. Tablelands	Alkaline Massifs	Low Hills Domain	Planed Surfaces	Granite Massifs	Gneiss Massifs	Coastal Islands
Supporting	Soil processes		X	X	X			X	X	X	X	X	X	X	X
	Habitat provision		X	X	X	X	X	X	X	X	X	X	X	X	X
	Platform for human activity	X	X	X	X				X		X	X			X
	Burial and storage	X	X	X	X	X	X		X		X	X			

The regulating services are displayed in Table 2. All services are provided by several units, highlighting the importance of geodiversity in providing ecosystem services within this category. Noteworthy are the roles of the mountains and hills as orographic barriers to rain clouds, the dunes in regulating water infiltration, the lagoons with Holocene stromatolites which store CO_2 and produce O_2, and the resurgence of the waters of the *Malvinas* Current, which influences the climate. Although atmospheric processes occur everywhere, only the units that interfere with these processes were marked.

The supporting services are displayed in Table 3, including the soil processes, habitat provision, use as platforms for human activity, and use for burial and storage. The supporting role is intrinsic to geodiversity, with some areas being used for environmental protection rather than human use. This is the case for the various protected areas in the GpCL territory, which exist in almost all of the mapped units.

Cultural services are presented in Table 4, which demonstrates the cultural value of the territory, particularly through human presence dating back to prehistory. The geological sites, many of which have international importance for science, have been the subject of artistic expression, whether through poetry or the visual arts. The territory was explored and described in publications by notable naturalists such as Charles Darwin, Auguste de Saint-Hilaire, and Charles Frederick Hartt, among others, in the 19th century. It is an area where sun and beach tourism predominates, but one that needs to promote a shift to a model that embraces regenerative development, allowing it to be better enjoyed by both residents and visitors.

Table 4. Cultural services in each geodiversity unit.

		Technogenic Units	**Marine Plains**	**Lagoonal Plains**	**Fluvial Plains**	**Dune Fields**	**Coastal Lagoons**	***Paraíba do Sul* River**	***Barreiras* Fm. Tablelands**	**Alkaline Massifs**	**Low Hills Domain**	**Planed Surfaces**	**Granite Massifs**	**Gneiss Massifs**	**Coastal Islands**
Cultural	Environmental quality		■	■	■	■	■		■	■			■	■	■
	Geotourism and leisure	■	■	■	■	■	■	■	■	■			■	■	■
	Cultural, spiritual and historical meanings	■	■	■	■	■	■	■	■						■
	Artistic inspiration	■	■	■	■	■	■	■	■	■			■		■
	Social development	■	■	■	■		■		■		■	■			
Cultural (knowledge)	Earth history	■	■	■		■	■	■	■	■				■	■
	History of research		■											■	
	Environmental monitoring and forecasting	■		■		■	■	■	■						
	Geoforensics		■												
	Education and employment	■		■	■	■	■	■	■						■

5. Discussion

Most published works on geodiversity mapping are based on quantitative evaluations, aiming to display information on the quantity of elements in a given area, e.g., [61–66]. However, as demonstrated by [67], qualitative methods have the potential to be applied in different contexts, such as land-use management and nature conservation. Therefore, this type of geodiversity mapping should be encouraged in order to better address methodological issues and to explore its potential. The goal of this article was to create a qualitative map of geodiversity and to use it to identify geodiversity-related ecosystem services, which is an aspect that has not been deeply investigated.

According to [68], the term geodiversity, by referring to the variety of elements, should be used as a parameter to measure diversity through statistical indices. We do not disagree with this perspective; however, understanding how the components of geodiversity interact with each other, originating different environments, is also of crucial importance. We therefore advocate for the use of the term geodiversity units as a basis for qualitative geodiversity mapping because it refers to the integration of the elements that compose the geodiversity of a given area. This represents a different use of the concept, focusing on the interactions of its components rather than using it solely as a measurement parameter. It is important to highlight that this perspective is not being presented here for the first time, as studies such as [11,12,67] presented similar approaches.

The qualitative method applied in this study revealed that the territory of the GpCL presents a high variety of environments, originating from the interactions among the various components of geodiversity. It is interesting to note that these interactions occur in different ways. For instance, the same type of geomorphology may be part of different units, as is the case with gneiss massifs and granite massifs, which differ significantly in terms of lithology. In other cases, the interactions are unique, as in the Marine Plains, where sand deposits formed by marine processes culminate in plains where Carbic Spodosols develop. These geological, geomorphological, and pedological units occur together exclusively, demonstrating a strong interdependence among these components.

A high number of geodiversity-related ecosystem services were found in the assessment, which highlights the importance of geodiversity in providing a wide array of benefits to human societies.

Concerning the provisioning services, all other services were identified in at least one geodiversity unit. Fishing activities occur in lagoonal, riverine, and coastal environments, many times being undertaken by traditional communities that live in the territory (Figure 7), and all the massifs are fundamental for providing water to the main rivers of the region, which are used, among other sources, for water supply. The coastal lagoons are historically used for salt production, which is also the reason for the development of the *salinas*, the main type of anthropogenic unit in the region. Fuel, construction minerals, ornamental products, and industrial minerals are extracted in several parts of the territory. In these cases, it is important to highlight that these activities may be responsible for environmental impacts, which demand special attention from decision-makers. The qualitative map of geodiversity associated with the ecosystem services analysis is a tool that can improve decision-making processes, enhancing the relevance of geodiversity within this context. Finally, plant fossils from the Pleistocene were recently found in some beaches of the territory.

Figure 7. Fishing community at *Baleia* Beach, one of the many traditional communities of the territory (photo: Kátia Mansur).

Considering the supporting services, the processes of soil formation and use, the provision of habitats for biodiversity, and the platform for human activities, including burial and storage, are included. Thus, practically all nodes in the matrix that relate this type of ecosystem service to geodiversity units are marked in Table 3, with few exceptions, generally related to legal prohibitions on occupation, such as dune fields, coastal islands owned by the Brazilian Navy, and bodies of water, such as lagoons and the *Paraíba do Sul* River.

Regulating services are usually strongly correlated to physical elements. Every geodiversity unit presents at least one service within this category. A strong example is the climate peculiarity in the southern part of the territory of the geopark, which is conditioned by the upwelling phenomenon that, in turn, is conditioned by the geological/geomorphological setting of the area. Another relevant example is flood regulation. Most of the coastline, especially in the south, is subjected to storm events, producing high energy waves and, eventually, provoking overwash processes. Geodiversity units such as the *Barreiras* Formation Tablelands, Marine Plains, and the dune fields are of great importance for providing protection to environments located further inland. With the ongoing climate changes, a higher frequency of these events is expected in the area.

Within this context, it is worth mentioning the threats related to sea-level rise due to global warming. While some geodiversity units are under threat, others are of crucial importance for the resilience of the region. The *Barreiras* Formation Tablelands, for instance, are related to cliffs that act as a barrier to wave action, something that would still occur in the case of sea-level rise. While coastal lowlands, especially in the Lagoonal Plains, may suffer severe impacts, the cliff-dominated coasts will experience much smaller impacts, as well as the environments "protected" by them.

Cultural services, which are also quite representative in the GpCL territory, are also threatened. Several cities and towns are located in coastal plains between rocky shores, making them vulnerable to rising sea levels or storm surges associated with extreme weather events. Many of these urban agglomerations have significant historical heritage, important archaeological sites, and populations that, in some cases, have been settled there since the 16th century. Many geosites of scientific, cultural, touristic, and educational significance are also subject to these effects.

6. Conclusions

The creation of qualitative geodiversity maps remains a subject in need of further investigation, as most existing mapping proposals are still focused on quantitative approaches. In this article, we argue that qualitative methods should prioritize understanding the interactions among the various components of geodiversity. This perspective allows for a deeper comprehension of the relevance of geodiversity elements, moving beyond the identification of areas with higher or lower diversity. Advancing qualitative geodiversity mapping can significantly contribute to expanding the possible applications of the concept.

The application of the map to the analysis of geodiversity-related ecosystem services was a valuable exercise, as it enabled the identification of several services that are fundamental to the local populations. The large number of services provided serves as evidence of the importance of geodiversity for the well-being of human societies, which depend on its components to thrive. Therefore, the method of associating geodiversity units with ecosystem services has proven to be a valuable tool for better understanding existing relationships.

Because of this, recognizing geodiversity as one of the pillars of territorial management is of utmost importance. In geopark territories, this recognition becomes even more relevant. Geodiversity units provide valuable information about how different elements interact, revealing both potentials and limitations for land use. They can also serve as a foundation for understanding environmental impacts, including those related to climate change. In the GpCL territory, for example, a potential rise in sea level poses a serious threat to several coastal environments. At the same time, it highlights the importance of certain geodiversity units due to their protective and resilient characteristics.

In conclusion, the integration of qualitative geodiversity mapping with the identification of ecosystem services represents a promising pathway for advancing geoconservation and territorial planning strategies. By revealing the complex interactions between abiotic elements and their influence on human activities, this approach enhances our understanding of landscape functionality and value. As global environmental challenges intensify, particularly in coastal regions like the GpCL, tools that connect geodiversity to social and ecological resilience become increasingly relevant. Future research should further explore these connections, strengthening the role of geodiversity in sustainability agendas at local, regional, and global scales.

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