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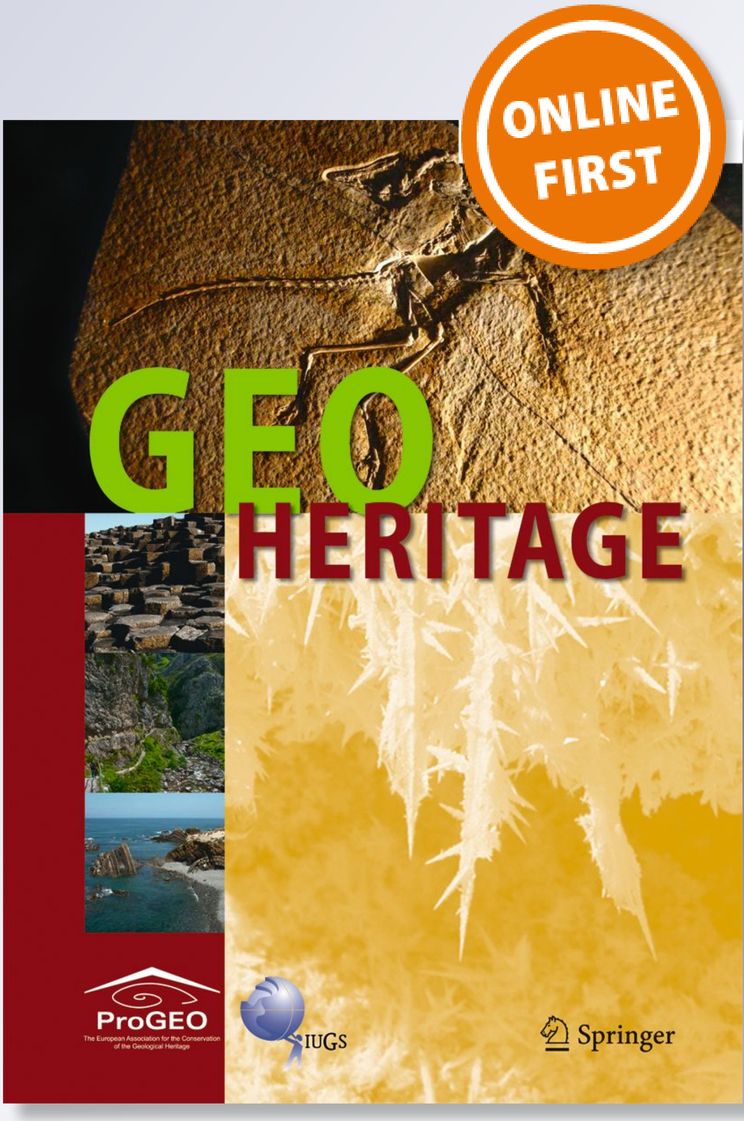
Geoheritage

ISSN 1867-2477

Geoheritage
DOI 10.1007/s12371-018-0295-y



Geoheritage
https://doi.org/10.1007/s12371-018-0295-y

ORIGINAL ARTICLE

Geodiversity Mapping and Relationship with Vegetation: A Regional-Scale Application in SE Brazil

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Received: 21 October 2016 / Accepted: 15 March 2018

Abstract

The natural variability of geological, geomorphological, pedological, and hydrological elements can be described and assessed in terms of geodiversity. This geodiversity is intrinsically linked to biodiversity, since the physical environment provides the conditions in which biological elements develop. The use of geodiversity as a tool for environmental studies is of growing importance, describing and highlighting the importance of the physical environment and strengthening the idea of holistic approach of the nature. This work consisted of a qualitative mapping of the geodiversity in Armação dos Búzios municipality, in Rio de Janeiro State, southeastern Brazil. Based on integration of the physical environment elements, geodiversity units were defined, in which the geological substrate, relief forms, and soil types are similar. The hydrological influence was also taken into account in specific units. Subsequently, each geodiversity unit was analyzed in terms of its regional type of vegetation, in order to investigate the correlation between spatial distributions of the physical and biological environments. As a result, a Geodiversity Map of Armação dos Búzios was created, describing the physical environment of the area. The inclusion of data on vegetation types showed direct correspondence of the Geodiversity Map and the biological environment, since each geodiversity unit is occupied by specific vegetation types. This result shows that the use of geodiversity as a tool to understand vegetation distribution patterns is valid and should be explored further within the contexts of land management and nature conservation. It is expected that this product becomes a tool for territorial management and an incentive for the development of furthermore research focused on holistic approaches to nature.

Keywords Geodiversity · Vegetation · Mapping · Territorial management

Introduction

Biodiversity conservation has become a key issue in the present context of global changes induced by human factors (Sala et al. 2000; Brooks et al. 2006). The increasing rate of resource utilization and the consequent severe environmental impacts are responsible for the "biome crisis" scenario (Hoekstra et al. 2005), with these threats to biodiversity having led to increased concern regarding protection of the remaining natural areas (Sarkar et al. 2006). Effective conservation plans are of paramount importance; however, they are often difficult to implement due to a lack of spatial biological data, which is difficult and expensive to acquire (Parks and Mulligan 2010; Hjort et al. 2012). Brazil is a prime example of these difficulties as it probably has the highest floral diversity in the world (Myers et al. 2000), yet, at the same time, it suffers from land management and nature conservation problems, due to the absence of data on biodiversity and its distribution, among other limitations.

In order to advance the creation of effective tools for nature conservation and planning, many researchers have been developing methods using indirect surrogates to understand biodiversity patterns (Franklin 1993; Zimmermann et al. 2007;

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Published online: 22 March 2018

Rochinni et al. 2010; Heinanen et al. 2012). The establishment of methods capable of determining priority areas for conservation is one of the main lines of research (Myers et al. 2000; Whittaker et al. 2005), and understanding the factors influencing the spatial distribution of biodiversity is essential to advance in this direction (Willis and Whittaker 2002). The use of non-biological information to help fill this lack of biogeographical data is valid; so, in this context, geodiversity has a good potential for use given its role in providing conditions for the development of biological elements. The intrinsic link between geodiversity and biodiversity can be explored in the development of models of geographical distribution patterns of biodiversity (Parks and Mulligan 2010). However, the concept of geodiversity is relatively new, and there are still methodological issues to be improved to effectively implement the use of geodiversity in conservation of biodiversity.

Gray (2013) defines geodiversity as "the natural range (diversity) of geological (rocks, minerals, fossils), geomorphological (landforms, topography, physical processes), soil and hydrological features. It includes their assemblages, structures, systems and contributions to landscapes". It is, therefore, the abiotic equivalent of biodiversity and plays a vital role in supporting the natural environment on which human societies depend (Prosser et al. 2010). The concept of geodiversity was first used in 1993, a year after the Convention on Biodiversity at the Earth Summit in Rio de Janeiro and has since been adopted in many countries (Gray 2011). Although there is no doubt as to the intrinsic relationship between geodiversity and biodiversity, conservation efforts still tend to treat them as separate entities, ignoring the essential linkages connecting biotic and abiotic environments (Matthews 2014).

Gordon et al. (2012), based on an ecosystem approach, highlight the importance of demonstrating the wider relevance and value of geodiversity as a fundamental basis of the ecosystem through its influence on landscape, habitats, and society. Understanding how the Earth system functions and understanding the relationships between physical, biological, and human factors are essential for successful implementation of a holistic approach to environmental management and nature conservation. Moreover, within this context, Gray et al. (2013) stated that engaging with the ecosystem approach would benefit the geosciences with new opportunities for research and applications and improved recognition of the value of geodiversity, leading to wider support for its conservation.

Given the scenario of environmental questions and management of the Earth's surface, the geosciences are making an effort to take a more holistic approach to knowledge of the planet, with the aim of contributing to a more sustainable way of life (Cordani 2000). Thus, taking into account the general lifestyle of industrialized countries, which is based on high rates of resource consumption, and the responsibility of creating a new paradigm for the relationship between nature and society, geoconservation is an emerging geoscience (Henriques et al. 2011), with the objective of promoting conservation of geological features by highlighting their importance to both society and biodiversity.

The concept of geodiversity is very important within geoconservation and can be applied in a number of ways and on different scales. This research consisted of qualitative mapping of geodiversity in the municipality of Armação dos Búzios, on the southeastern coast of Rio de Janeiro State, Brazil. Geological, geomorphological, pedological and, in some cases, hydrological elements were analyzed in an integrated manner based on a landscape approach, resulting in the creation of geodiversity units. These units were subsequently analyzed according to their regional vegetation types, in order to investigate the correlation between the physical and biological features of the environment.

The relationship between physical and biological features is not a new theme and has been one of the main aims of biogeographical research for decades (Hjort et al. 2012). However, the use of geodiversity in its full scope is very recent, and there are few published studies, especially on relationships with biodiversity, (e.g., Jacková and Romportl 2008; Parks and Mulligan 2010; Brazier et al. 2012; Hjort et al. 2012; Anderson et al. 2015). Due to the potential contribution of geodiversity to understanding biodiversity distribution patterns and building species predictive models, among other applications, further research on methodological issues in geodiversity is of paramount importance.

Geodiversity and Territorial Management

With the emergence of Environmental Geology, the concept of *landscape* has become more relevant in geological studies. Fundamental terms like *sustainability* and *exhaustion of natural resources* are being used more and more, demonstrating a more holistic/systemic approach in these studies, as well as better integration with specialists in different fields (Keller 1996; Cordani 2000). The geosciences as a whole are growing in importance for society and studies of the physical environment focused on subsidizing territorial management policies can be highlighted, among other applications.

With the concept of geodiversity, the geosciences developed a new and effective tool for landscape analysis. The integrative approach to physical environment, inherent to the concept, is of paramount importance for territorial planning and management and for nature conservation strategies (Dantas et al. 2015). Adamy (2015) highlights the importance of geodiversity as the substrate in which biodiversity develops and human activities take place. Therefore, in order to precisely establish a territorial management policy concerned with sustainable development and nature conservation, it is fundamental to understand geodiversity and its relationship with biological and anthropic environments (Fig. 1).

The Geological Survey of Brazil (CPRM—*Companhia de Pesquisas de Recursos Minerais*) has been focusing on a holistic approach to environmental studies over the last decades. Corrêa and Ramos (1995) were pioneers in developing a Geoenvironmental Map in the municipality of Morro do Chapéu (Bahia State, NE Brazil), consisting of an integration of geology, geomorphology, soils, hydrography, vegetation, and land use information. It was followed by Dantas et al. (2001) in the creation of a similar product for the entire State of Rio de Janeiro. These maps are examples of holistic approaches within the context of landscape analysis, bringing together elements of geodiversity, biodiversity, and human factors. However, they did not consider the concept of geodiversity in their work.

In 2007, the CPRM published the Geodiversity Map of Brazil, at a scale of 1/2,500,000 (CPRM 2007), describing the major geosystems of the national territory. By describing the geological setting and influence of other elements of the physical environment, such as geomorphology, soils, and hydrology, this map defined the main limitations and potentialities in view of use and occupation of each unit. The practical use of this product was limited due to its very small scale and overemphasis on geological elements to the detriment of geomorphological and pedological elements, which should be equally important on geodiversity maps. However, it was the first in the country to implement the concept of geodiversity directly to territorial management issues.

Subsequently, the CPRM began systematically mapping geodiversity in each state of the country, at more refined scales. The aim of these maps is to provide scientific-geological knowledge of the territory to all sectors of society, such as mining companies, the academic community, and territorial and environmental managers. The entire product is composed of information on the physical environment as a whole; geotechnical characteristics, availability of water resources, and vulnerabilities and capacities in the face of different human activities. Besides the abovementioned, other specific areas are being mapped, following the same method. All these publications are available on the CPRM website (http://www.cprm.gov.br/publique/Gestao-Territorial/Geodiversidade-162; in Portuguese).

Relationship Between Geodiversity and Biodiversity

There is an intrinsic relationship between geological and biological diversity, and geodiversity can be considered the foundation of the ecosystem (Santucci 2005). Gray et al. (2013) stated that the geodiverse nature of the Earth is responsible for

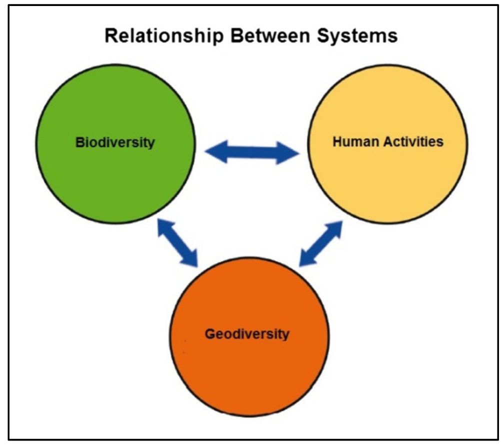

Fig. 1 Relationship between geodiversity, biodiversity, and human activities (Modified from Adamy (2015))

the range of ecosystem services, thereby highlighting the importance of the abiotic nature in ecosystem management as a whole. The concept of ecosystem, as described in Tansley (1935), comprises not only the organism-complex but also the entire complex of physical elements. In other words, there is no clear separation between geodiversity and biodiversity, and this is a fact that is not always taken into account in environmental planning and management.

Whittaker (1972) describes habitats as "the environment of a species, as characterized primarily by physical and chemical qualities […]." The author also states that the evolution of species tends to move towards differentiation of habitats in order to reduce competition. In this sense, each species added to the biota of a landscape fits itself into a habitat that is different from those of other species. Therefore, the diversity of physical and chemical conditions of the environment may be responsible for potentially supporting the development of different habitats. In other words, a more varied landscape would enable an increase in biodiversity.

Barthlott et al. (2007) also highlight the role of geodiversity as a driving mechanism for habitat variation, which would indicate greater biodiversity in more geodiverse areas. Each element of the physical environment influences the development of organisms, whereby, rock types may provide different kinds of nutrients (e.g., Moser et al. 2005); geomorphological diversity is an important factor controlling the variability of habitats (e.g., Burnett et al. 1998); and both geology and geomorphology influence the soil, which will, in turn provide resources for biological elements (Parks and Mulligan 2010). It is thus expected that an analysis of geodiversity has the potential to be integrated into biodiversity studies, contributing to understanding distribution patterns and the effects of environmental changes.

Geodiversity is a relatively new subject, and research focused on the relationship with biodiversity remain uncommon. However, during the last decade, some important studies have been published, showing that this theme is passing through a moment of development and consolidation. Most of these articles present quantitative approaches, investigating whether an increase in geodiversity would lead to increased biodiversity.

Jacková and Romportl (2008) performed a statistical correlation between geodiversity and habitat richness, with the hypothesis that high geodiversity would be related to high habitat richness. The authors presented a methodology for quantitative assessment of geodiversity considering the geological setting and several topographic and hydrographic parameters, identifying the least and most geodiverse areas. The authors confirmed the initial hypothesis through correlation with a habitat richness map.

Another interesting approach is presented by Parks and Mulligan (2010), who developed a model of geodiversity assessment in which the elements of geodiversity were considered in terms of their resource-giving potential and the spatial and temporal variation of the said resources. According to the mentioned authors, the development of biodiversity requires high spatial and temporal variability of resources, enabling coexistence without competition and facilitating specialization and endemism.

Both of the studies mentioned above (Jacková and Romportl 2008 and Parks and Mulligan 2010) advanced on the idea that geodiversity is directly related to biodiversity. However, there are still conceptual issues to be addressed. Pellitero et al. (2014) stated that geodiversity can be assessed directly, by computing existing classes of geodiversity, such as rocks, soils, and landforms, or indirectly by using indicators which are usually related to geodiversity, such as altitudinal range, aspect of slopes, and roughness of terrain, among others. This difference is crucial in any geodiversity assessment, since parameters like topography are not directly related to geodiversity.

Hjort et al. (2012), investigating whether geodiversity could improve the explanatory and predictive power of species richness models, presented an interesting conceptual approach, treating explicit measures of geodiversity (geology, geomorphology, and hydrology) and topographic and climatic parameters separately. The results showed good correlation between geodiversity and biodiversity, since the inclusion of direct measures of geodiversity was able to improve species richness models. This was a very important contribution not only for strengthening geodiversity as a surrogate for biodiversity but also for providing this conceptual approach, highlighting that the practical applications of geodiversity must be linked to the theoretical concept.

Quantitative approaches are of paramount importance for the development of geodiversity as a surrogate for biodiversity, but the qualitative approaches also can play a crucial role in this context. The simple idea that different organisms will occupy different areas according to geological, geomorphological, and pedological settings is enough to improve land management and conservation planning. Exploring the idea that geodiversity and biodiversity are essentially linked remains a challenge, since abiotic and biotic natures are often treated as separate entities (Matthews 2014).

Several case studies in which geodiversity was successfully incorporated into conservation plans are presented in Anderson et al. (2015). Hjort et al. (2015) also presented the importance of geodiversity for biodiversity conservation, showing that sites with different geological settings, such as caves, sand dunes, or river bars, harbor unique biotas. Another interesting example is presented by Bétard (2013), who focused on the spatial relationship between geodiversity and biodiversity patterns in a disused quartzite quarry. The heterogeneity created by quarrying created a diversity of ecological niches, showing that even human induced changes in geodiversity can induce rapid adjustment of the biological elements.

Quantitative and qualitative studies on the relationship between geodiversity and biodiversity have shown that interesting results can be achieved, improving land management and nature conservation efforts. Some important issues must be taken into account, such as (1) a clear definition of the concept of geodiversity, (2) a proper practical application of the concept, and (3) the scale of the work. These issues must be clear in order to contribute to improvements to the theory and methodology of geodiversity.

Study Area

The study area of is the municipality of Armação dos Búzios, which is located on the southeastern coast of Rio de Janeiro State, Brazil (Fig. 2). It has many coves and beaches of great scenic beauty and, as such, is one of the most important touristic destinations in Brazil, being the fifth most visited place by foreign tourists to the country. The area of the municipality can be divided into two main units, the peninsula and the continental area, which are connected by a tombolo.

Geodiversity

The geological setting of Rio de Janeiro State is determined by its location in the central part of the Ribeira Belt, which has its origins in the Gondwana amalgamation and, in this sector, is divided into four tectonic domains: the Occidental Terrane; the Paraíba do Sul Domain; the Oriental Terrane; and the Cabo Frio Tectonic Domain (CFTD), as described by Heilbron and Machado (2003). However, Schmitt et al. (2008) argue that the CFTD has African affinities and is not a part of the Ribeira Belt. The study area is located entirely in this domain.

The CFTD probably represents the last episode of the Gondwana amalgamation, in a 530–490 Ma

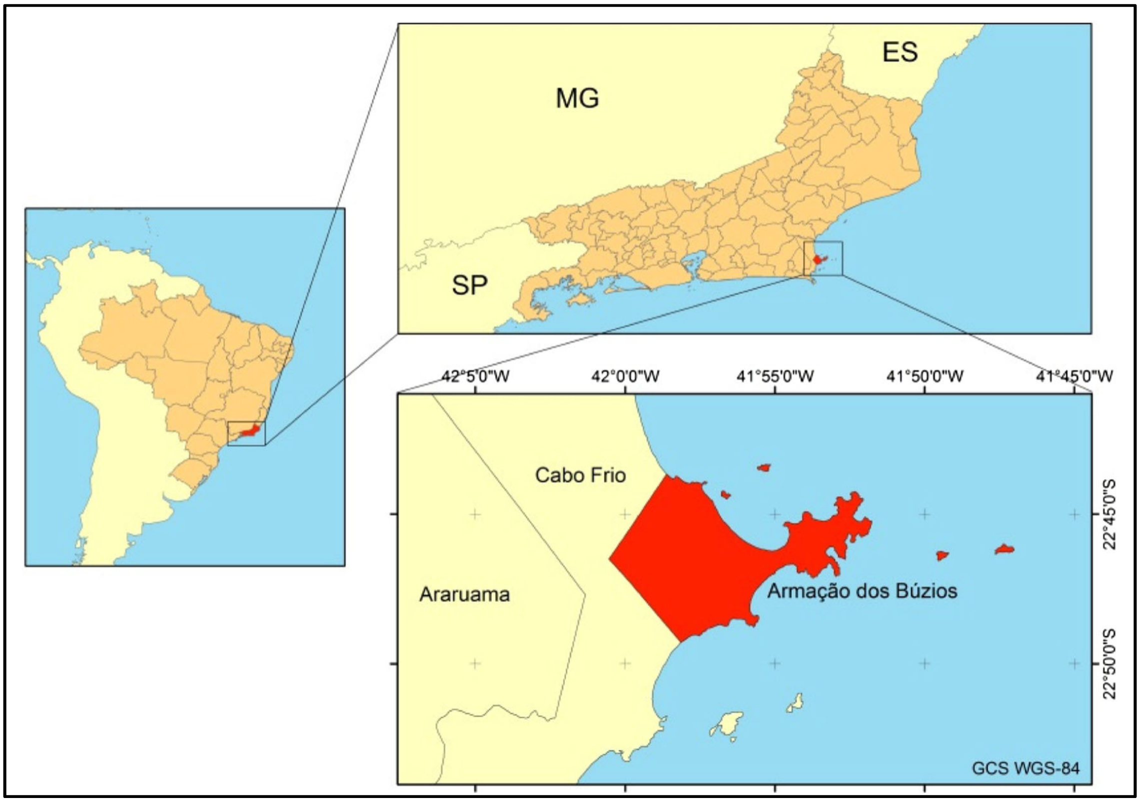

Fig. 2 Location of the study area (Armação dos Búzios municipality)

tectonometamorphic event called Búzios Orogeny. It is composed of supracrustal rocks of Neoproterozoic–Cambrian age related to an ocean basin (Búzios-Palmital Basin), tectonically interleaved with a reworked Paleoproterozoic basement (Schmitt et al. 2004). The reworked basement is predominantly composed of felsic orthogneisses, represented by the Região dos Lagos unit, which is intruded by amphibolite tabular bodies from the José Gonçalves Suite. The Neoproterozoic succession is composed of metavolcanic rocks of the Forte de São Mateus unit (amphibolites) and metasedimentary rocks of the Búzios unit (paragneisses), associated with the Búzios–Palmital Basin. The occurrence of Mesozoic dykes registers the Gondwana breakup and the Atlantic Ocean opening events. Sedimentary rocks from the Neogene, called the Barreiras Formation, occur in some portions of the area, as result of fluvial processes of high energy, like alluvial fans. Different Quaternary sedimentary deposits are also present in the area, related to gravitational, marine, and eolian processes (Fig. 3a).

The geological diversity of the area is responsible for the high geomorphological diversity. The Quaternary deposits are related to the Beaches and Marine Plains (formed by marine processes), Dunes (formed by eolian processes), Colluvium and Alluvium–Colluvium Ramps (formed by gravitational processes) and Swampy Areas (formed by colmatation of lagoons after the last drop in sea-level); Medium Hills and Hills with Steep Slopes that are mainly associated with the paragneisses of the Búzios unit; Low Hills with Gentle Slopes and Planed Surfaces that are distributed along the continental area, related to highly weathered orthogneisses of the Região dos Lagos unit; and a Linear Ridge in the south, which is the most prominent relief form of the municipality, associated with a thrust fault (Fig. 3b).

Different soil types are distributed according to the geological and geomorphological setting. The Marine Plains are composed of carbic spodosols and quartzarenic neosols. Yellow and red-yellow ultisols occur in the Low Hills with Gentle Slopes of the continental area. Associations of red ultisols and chromic luvisols, together with occurrences of cambisols, occupy the areas of Medium Hills, Hills with Steep Slopes, and the Linear Ridge. The Planed Surfaces are composed of haplic albaqualfs; and melanic gleysols and hydromorphic albaqualfs occur in the Swampy Areas. There are also some occurrences of yellow oxisols in the peninsula area, associated with hills with lower declivities (Fig. 3c).

There are no permanent rivers in the municipality of Armação dos Búzios, and the hydrographical network is restricted to intermittent drainage flows. There are many lagoons and wetlands, especially in the continental area (Fig. 3d). Most of these areas are related to relative sea-level fluctuations during the Holocene. About 5100 years BP, the relative sea level was higher than at present (Turcq et al. 1999; Castro et al. 2014), and, in this context, barrier-lagoon systems were developed in the area. Subsequently, despite two minor

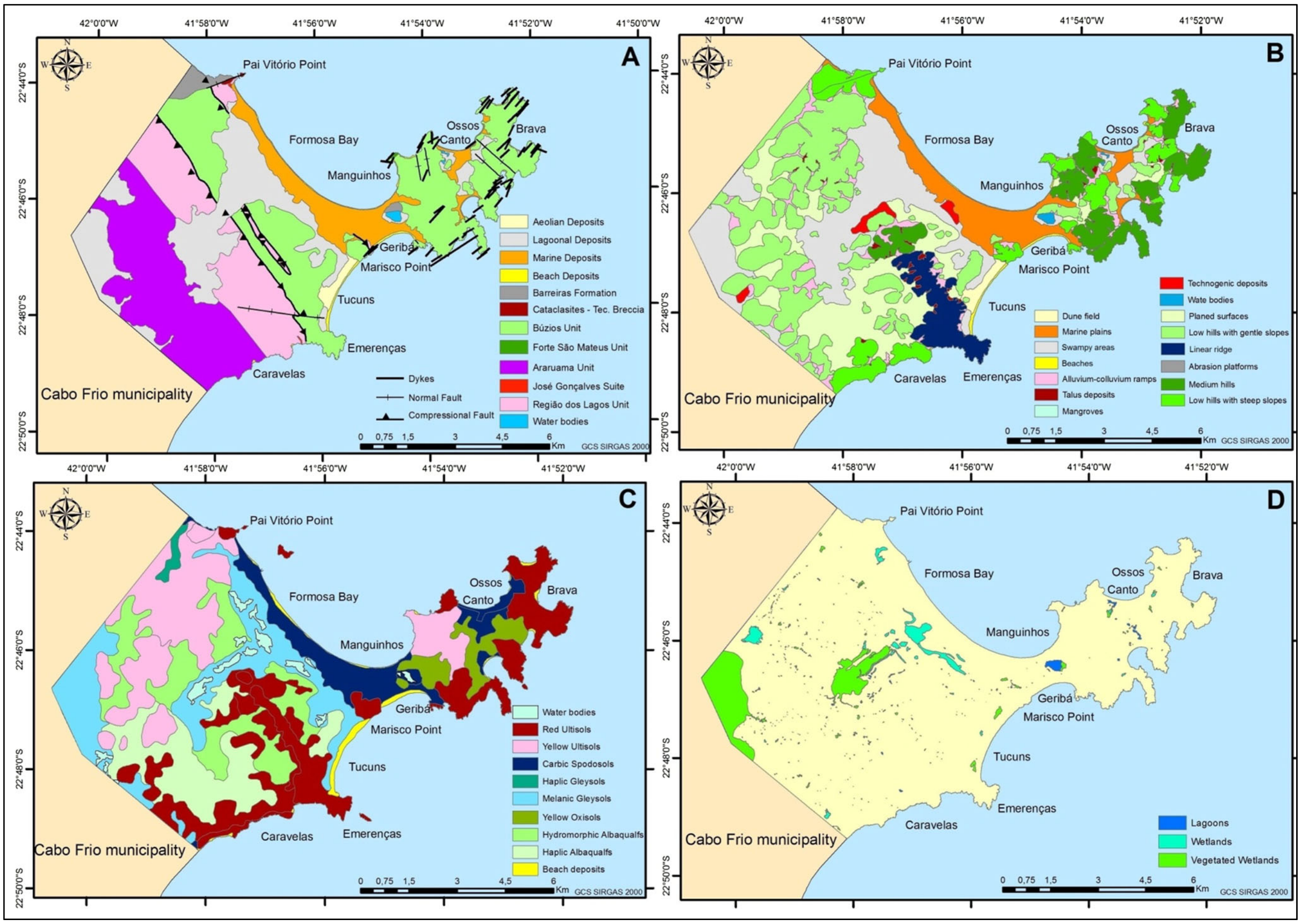

Fig. 3 **a** Geological map (modified from Schmitt et al. 2009; Tetzner 2002); **b** geomorphological map; **c** soil map (modified from Lumbreras et al. 2001); hydrographic map (modified from Mansur et al. 2006)

oscillations, the sea level has been progressively dropping along the coast of Rio de Janeiro State, which resulted in a tendency of transformation of lagoons into swampy areas, as described in Martin et al. (1996).

Vegetation

The Armação dos Búzios is entirely located in the Cabo Frio Center of Plant Diversity, which is characterized by unique floristic and physiognomic diversity, with a high degree of endemic species (Araujo 1997). The influence of the ocean and the local conditions of the physical environment are key factors in determining the variety of vegetation types, which, according to Dantas et al. (2009) and Bohrer et al. (2009), consists of the following: semi-deciduous seasonal forest, seasonal dry forest, sandbank vegetation, hydrophytic vegetation, and dune pioneer vegetation.

The map presented in Fig. 4 is modified from Dantas (2005), who mapped the vegetation types at a scale of 1:30,000, with additional information provided by Bohrer et al. (2009), who created a potential vegetation map for the entire Cabo Frio Center of Plant Diversity. The mangrove areas mapped by Mansur et al. (2006) and the occurrence of Dune Pioneer Vegetation, mapped in the present study, were also included. This Potential Vegetation map provides information on the distribution of vegetation types throughout the area without land use modifications from human activities.

Semi-deciduous seasonal forests are the result of the annual variance of rainy and dry seasons. Despite the floristic similarities with the Atlantic rainforests of other regions, the species of semi-deciduous seasonal forests have undergone morphological and physiological adaptations due to the lack of water resources in the region; seasonal dry forests present very high physiognomic heterogeneity, with trees occupying humid and wind-protected areas, and xeromorphic shrub vegetation occupying exposed areas; sandbank vegetation can be divided into sandbank forests and shrub-herb sandbank vegetation, according to physiognomic variations; hydrophytic vegetation occurs on the wetlands and is adapted to the oxygen-deficient substrates; and the dune fields are occupied by dunes pioneer vegetation.

In addition, there are three small but special occurrences of mangrove in the municipality, which differ from the traditional mangrove areas of southeastern Brazil as the substrate is

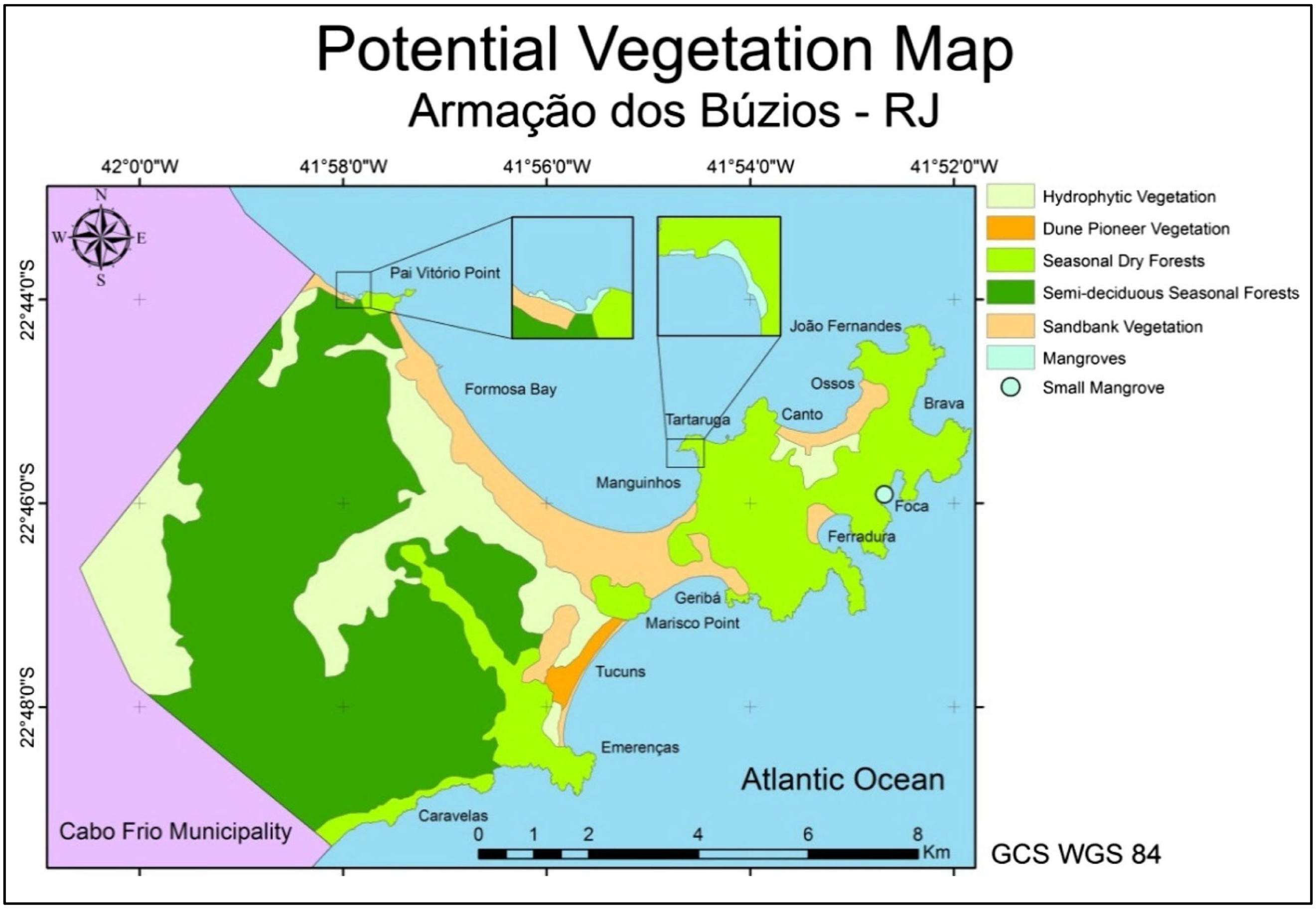

Fig. 4 Potential vegetation map of Armação dos Búzios. Modified from Dantas (2005), Mansur et al. (2006), and Bohrer et al. (2009)

composed of stones and coarse sand (traditional mangroves have mud substrates). For this reason, these areas received a local colloquial name, stone mangroves (in Portuguese: *Mangue de Pedra*), which is now used not only by the population but also by researchers. This mangrove system is a very rare environment in Brazil and in the world, as there are few descriptions of similar occurrences. The mangrove in these areas is sustained by fresh underground waters that discharge in coastal areas protected from the waves (Mansur et al. 2006).

Methodological Procedures

This work consisted of the creation of a geodiversity map of Armação dos Búzios through the definition of units that are similar in geological, geomorphological, pedological, and hydrological attributes. The first step was the creation of a geomorphological map of the area (scale 1:25,000), which was used as the basis for the geodiversity map, which was achieved by integrating geological, pedological, and hydrological information available in previous studies on the area, as follows:

- Geological map, scale 1:25,000 (modified from Schmitt et al. 2009; Tetzner 2002);
- Soil map, scale 1:50,000 (Lumbreras et al. 2001);
- Map of hydric resources and mangroves, scale 1:10,000 (Mansur et al. 2006);
- Map of rocky outcrops, scale 1:10,000 (Mansur et al. 2006).

Geomorphological Map

The methodology to create the geomorphological map of Armação dos Búzios, scale 1:25,000, was that one used by the CPRM, described in Dantas (2013). It is based on the concept of *Relief Pattern* (Ross 1990), which refers to the identification and spatial representation of relief forms with similar morphologies. This methodology was developed to enrich geodiversity maps with more detailed geomorphological information and is supposed to be practical and easily reproduced in order to be applied in territorial management issues.

The first step consisted of the use of remote sensing data for a preliminary definition of units with similar morphologies:

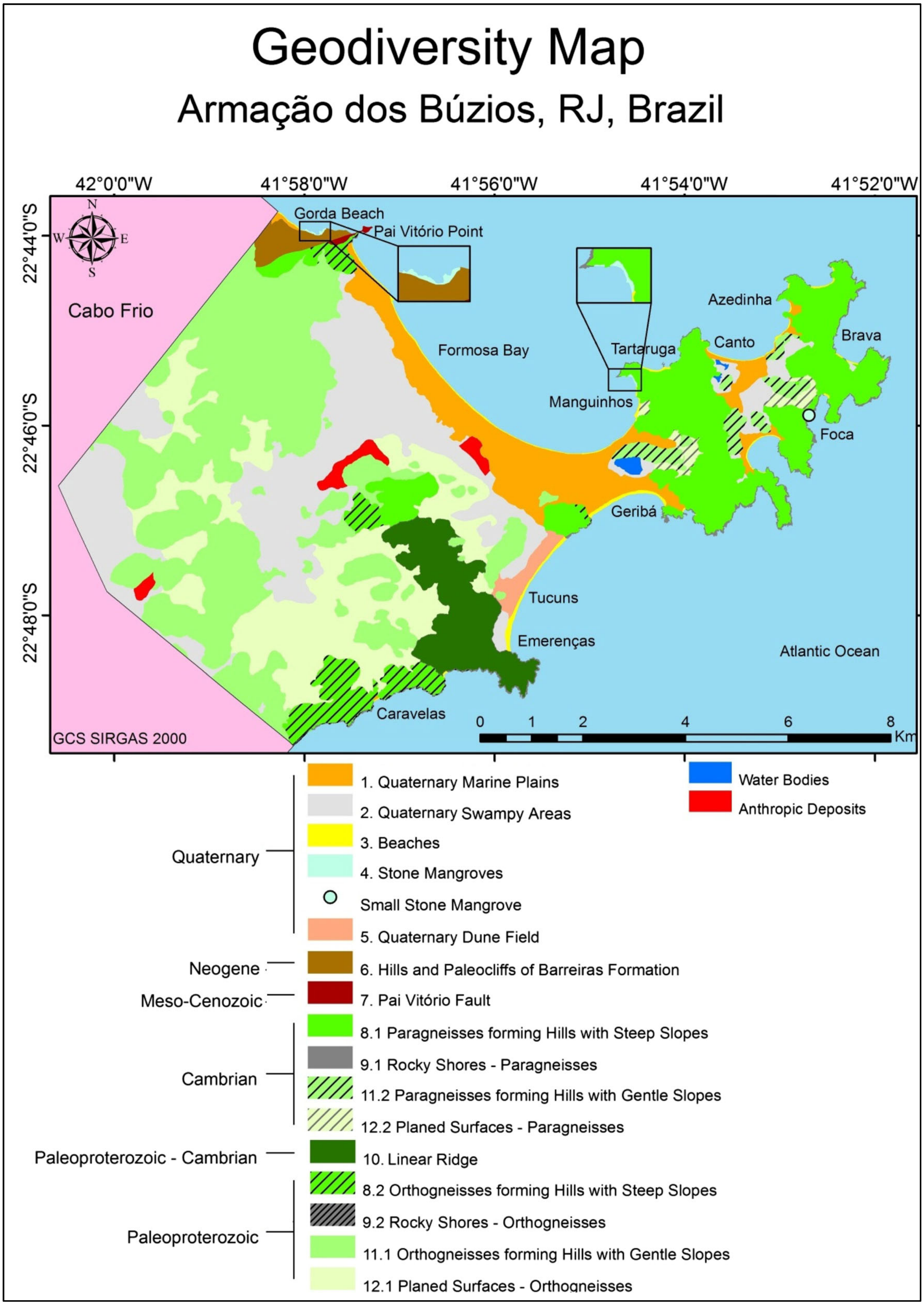

Fig. 5 Geodiversity map of the Armação dos Búzios, RJ State, Brazil

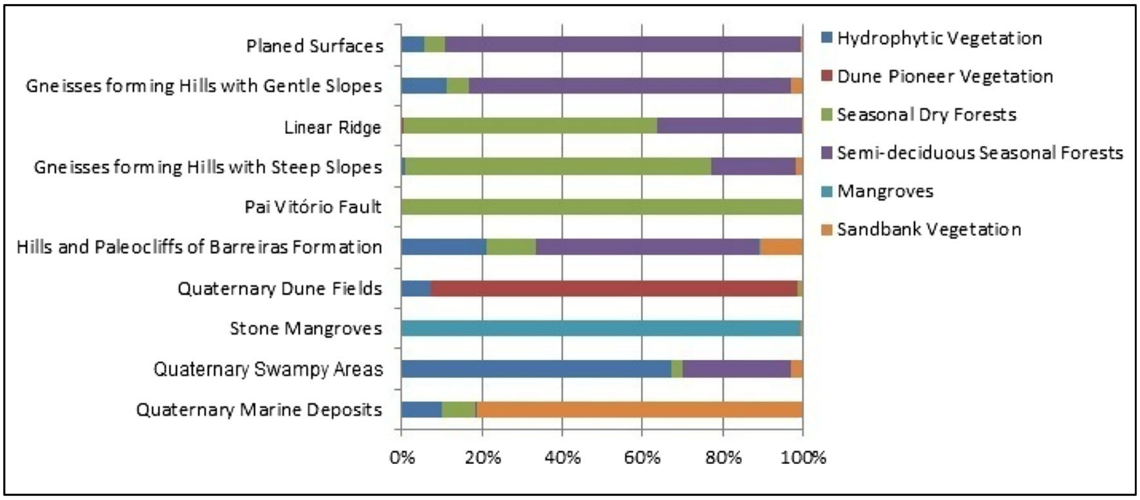

Fig. 6 Correlation between geodiversity units and vegetation types

- Aerial photographs—scale 1:25.000, available on the IBGE (Brazilian Institute of Geography and Statistics) website;
- Satellite images—Landsat 8, available on the INPE (National Institute for Spatial Research) website;
- Digital elevation model—1-m resolution, provided by the Armação dos Búzios City Council.

The main parameters analyzed were as follows: altitudinal range, declivity, and slope curvature. With the software ArcGis 10.0, DEM was used to generate maps to support interpretation (hypsometric, declivity, curvature, and hillshade). The geological and soil maps were also used, since the geomorphological units are intrinsically linked with these features.

The second step consisted of field surveys, with the aim of evaluating and refining the preliminary map, solving specific questions that were impossible to define through remote sensing techniques. Morphometric analyses were undertaken with the use of hypsometer (*Laser Tech Trupulse 360R*) to confirm or modify classifications based on the DEM and also for a better description of the geomorphological units. Soil analyses were also performed, these being essential to precisely define the limits between different Quaternary units, like marine

Table 1 Synthesis of the geodiversity units and associated vegetation types

Geodiversity unit	Geology	Geomorphology	Soils	Vegetation
Quaternary marine plains	Marine sand deposits	Marine plains	Carbic spodosols/quartzarenic neosols	Sandbank vegetation
Quaternary swampy areas	Paleolagoon deposits	Swampy areas	Melanic gleysols/hydromorphic albaqualfs	Hydrophytic vegetation
Beaches	Marine sand deposits	Beaches	Sand deposit	No vegetation associated
Stone mangroves	Boulders and coarse sand deposits	Mangroves	Stones and coarse sand	Mangroves
Quaternary dune field	Quartz-sand eolian deposits	Dunes	Sand deposit	Dune pioneer vegetation
Hills and paleocliffs of Barreiras Formation	Conglomerates and sandstones	Hills with steep slopes/hills with gentle slopes	Yellow and red-yellow ultisols	Seasonal dry forests/semi-deciduous seasonal forests
Pai Vitório Fault	Cataclasites and tectonic breccia	Hills with steep slopes	Cambisols/red ultisols	Seasonal dry forests
Gneisses forming hills with steep slopes	Paragneisses/orthogneisses	Hills with steep slopes	Red ultisols/chromic luvisols/cambisols	Seasonal dry forests
Rocky shores	Paragneisses/orthogneisses	Hills with steep slopes	Rocky outcrops	No vegetation
Linear ridge	Paragneisses/orthogneisses	Linear ridge	Red ultisols/cambisols	Seasonal dry forests/semi-deciduous seasonal forests
Gneisses forming low hills with gentle slopes	Orthogneisses/paragneisses	Hills with gentle slopes	Yellow and red-yellow ultisols/yellow oxisols	Semi-deciduous seasonal forests
Planed surfaces	Orthogneisses/paragneisses	Planed surfaces	Haplic albaqualfs/yellow oxisols	Semi-deciduous seasonal forests

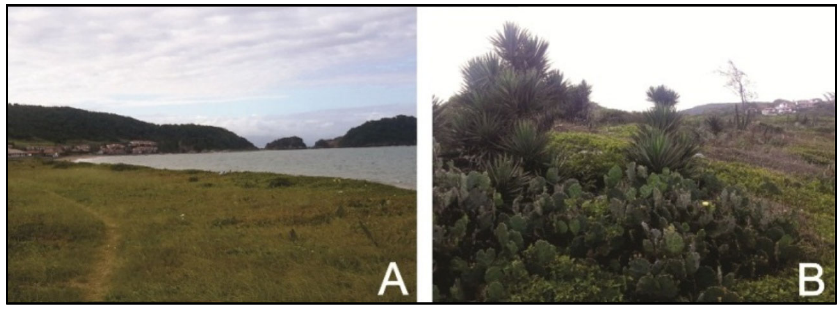

Fig. 7 **a** Marine plains occupied by the sandbank vegetation. The marine sand deposits are well-drained terrains in sub-horizontal surfaces, with **b** vegetation varying from grasslands and shrub-herb vegetation to forests

plains and swampy areas, which are very similar in their topography, but very different in their composition.

It was therefore possible to create the geomorphological map of Armação dos Búzios, scale 1:25,000, which was used as a basis for the creation of the geodiversity map of Armação dos Búzios, with the inclusion of more detailed geological and pedological information in the analysis.

Geodiversity Map

The geodiversity map was created through the integration of geological and pedological information with the geomorphological map, based on the idea of holistic approaches to environmental studies and taking into account the theoretical concept of geodiversity. Hydrological information was also used in the definition of units where hydrological features had strong influence on the environment, such as beaches and rocky shores.

The geological, geomorphological, and pedological maps were overlaid for a preliminary analysis, which was an important first step enabling the observation of the main patterns and associations between the elements (ex: marine deposits–marine plains–spodols/neosols or paragneisses–hills with steep slopes–red ultisols/chromic luvisols).

The geodiversity units were then defined, described, and classified according to its stratigraphic characteristics, giving rise to the geodiversity map of Armação dos Búzios.

The geodiversity map enabled investigation of possible correlations between geodiversity and vegetation types. The geodiversity map was overlaid with the potential vegetation map, for an initial observation of the relationship between the distribution of the geodiversity units and the vegetation types throughout the area. The differences in scale produced a few inconsistent results, which were solved by considering the full description of the vegetation presented by the authors of the vegetation maps and analyses during the fieldwork.

This work was undertaken on a landscape-scale analysis and is therefore restricted in correlating the geodiversity units with the regional vegetation types described on the Potential Vegetation Map of Armação dos Búzios (Fig. 4). Deeper investigation was not possible due to a lack of data on species richness and diversity. As a result, biodiversity, as described in Whitaker (Whittaker 1972), could not be assessed since it would require more detailed information on species diversity and not only spatial distribution of vegetation types. However, the phyto-physiognomic and floristic differences between the vegetation units were considered sufficient to present the influence of geodiversity on vegetation in a qualitative manner, which was the main purpose of this work.

Results

The geodiversity map of the Armação dos Búzios (Fig. 5) displays an integrated analysis of the physical environment and, together with information on the types of vegetation, presents a holistic approach to the diversity of nature.

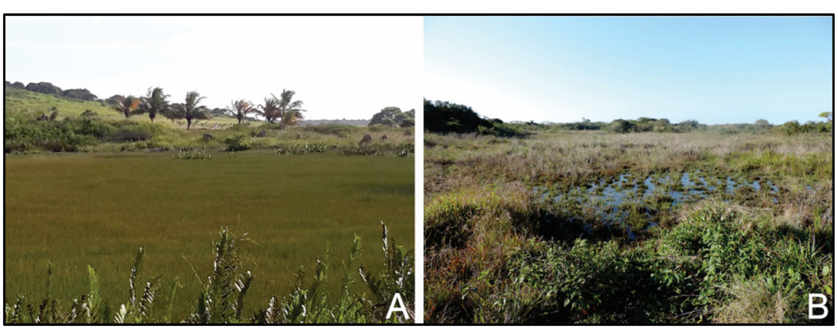

Fig. 8 **a** Swampy areas, which are plains with no topographic variations and **b** wetlands occupied by hydrophytic vegetation. These flat lowlands are subject to permanent or temporary flooding. This condition is the main reason for the predominance of hydrophytic vegetation in this unit, which is mainly composed of grasslands

Fig. 9 Geribá (a) and Tucuns (b) beaches. The direct influence of the ocean on these marine sand deposits prevents the development of any kind of vegetation

The overlaying of the geodiversity map with the potential vegetation map enabled quantification of areas combining geodiversity units and vegetation types (Fig. 6), which was an important step in presentation of the main associations. The results presented in Table 1 show a synthesis of the geodiversity units and vegetation types associated with each one.

Quaternary Marine Plains

This unit consists of Quaternary marine deposits, forming marine plains with carbic spodosols and quartzarenic neosols. In Fig. 7a, it is possible to observe the characteristic sub-horizontal relief of this unit, with small declivities reaching no more than 5°. This unit is occupied by the sandbank vegetation, which, as shown in Fig. 7b, increases in height with distance from the sea.

Quaternary Swampy Areas

The origin of this unit is related to sea-level variations in the Holocene. During the last great marine transgression, about 5100 years BP, barrier-lagoon systems were developed, and with the following regression, these lagoons passed through a process of colmatation, with the remaining paleolagoon deposits forming totally flat plains, with no surface variation, as shown in Fig. 8a. The plains are composed of melanic gleysols, with some small occurrences of hydromorphic albaqualfs. In Fig. 8b, it is possible to observe that most of the terrain is permanently flooded, so the vegetation is adapted to this condition, consisting of hydrophytic vegetation.

Beaches

The influence of the ocean was the main parameter in the definition of this unit, which consists of marine sand deposits under direct influence of waves, currents, and tides and being characterized by intense morphodynamic processes. The influence of the ocean prevents the development of pedogenetic processes, and vegetation is absent, as observed in Fig. 9.

Stone Mangroves

The stone mangroves unit occurs in three areas: at Gorda beach (the most prominent mangrove in the area—

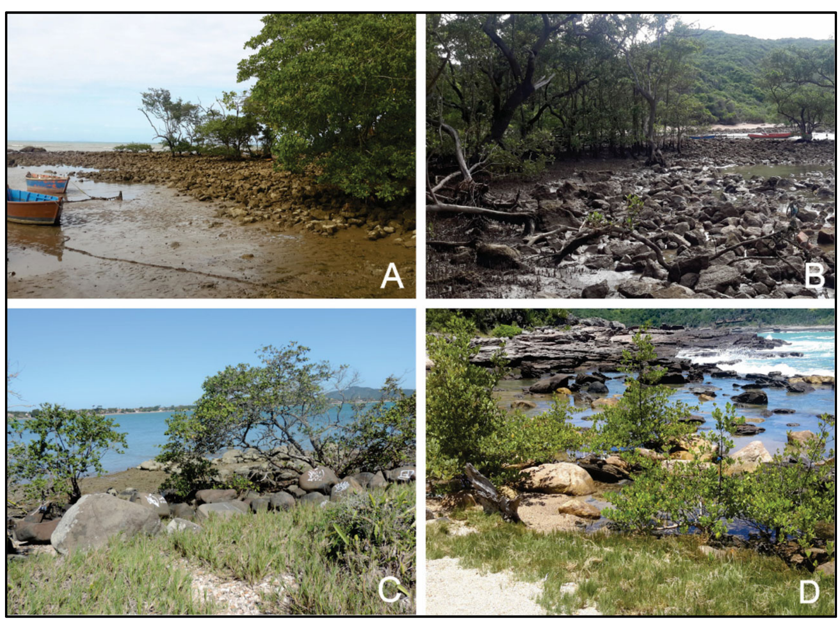

Fig. 10 a and b Stone mangrove at Gorda beach; c Manguinhos; d small mangrove at Foca beach. It is possible to observe that these mangrove vegetation occurrences are different from the traditional mangroves because of their substrate (mainly composed of stones and coarse sand)

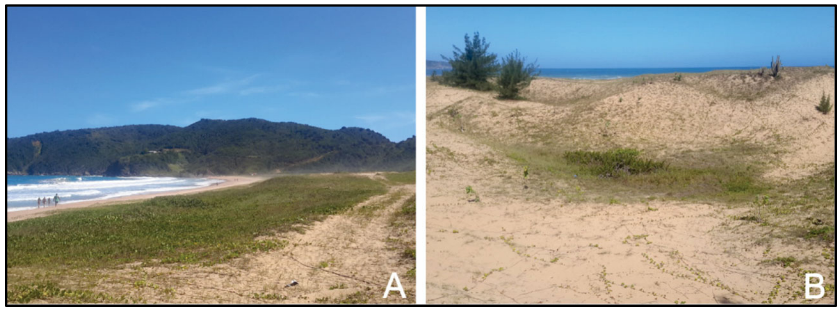

Fig. 11 Dune fields of Tucuns occupied by herbal species of the dune pioneer vegetation

Fig. 10a,b); at Manguinhos beach (Fig. 10c); and a physiognomically small formation at Foca beach (Fig. 10d).

It is possible to observe in Fig. 10 that these formations differ from the traditional mangrove areas owing to the specific geological conditions: the substrate not being composed of silt/clay, but of stones and coarse sand. The mangrove occurs because of fresh underground water discharging in coastal areas protected from the waves. These stone mangroves illustrate a specific case of the relationship between geodiversity and biodiversity, since local lithological, hydrological, and geomorphological conditions are responsible for the setting of a vegetation type which is totally different from the main types of the region.

Quaternary Dune Field

There is only one dune field in the area, in the region of Tucuns. This formation consists of eolian deposits of very well sorted quartz-sand. It is occupied by a specific vegetation type called dune pioneer vegetation, which represents the first step of ecological succession, being mainly composed of herbal species (Fig. 11), which also helps to secure the natural movement of the dune.

Hills and Paleocliffs of Barreiras Formation

This unit is related to the Neogene sedimentary rocks of the Barreiras Formation, composed of stratified conglomerates in this section (Fig. 12a). The relief consists of hills with steep slopes and areas with gentle slopes, with the presence of small cliffs. There are also paleocliffs, developed at moments of marine transgression during the Quaternary (Fig. 12b). Yellow and red-yellow ultisols prevail, and the vegetation types occupying this unit are seasonal dry forest in the steeper areas and semi-deciduous seasonal forests in the gentle-sloped areas.

Pai Vitório Fault

An extensional fault of Mesozoic age (Pai Vitório Fault) marks the boundary between the Barreiras Formation and the orthogneisses of the Região dos Lagos unit. It was reactivated during the Cenozoic and has formed cataclasite and fault breccia, developing a relief form of hill with steep slopes aligned with the fault (Fig. 13a), overlain by cambisols and red ultisols. The declivity and soil types decrease the capacity to store water, creating conditions for the development of Seasonal Dry Forests in the area, with the presence of endemic cacti species on the slopes facing towards the sea (Fig. 13b).

Gneisses Forming Hills with Steep Slopes

This unit is divided into two subunits due to lithological differences. It consists of hills with steep slopes, sometimes above 45° (Fig. 14a), usually distributed along the coast and mainly associated with the metasedimentary rocks of Búzios unit, but with occurrences associated with the orthogneisses of the Região dos Lagos unit, outside the peninsula area. The rocks of this unit are cut by Mesozoic dykes. Due to the high declivities, the soils are not deep (Fig. 14b), with red ultisols, chromic luvisols and cambisols prevailing. The vegetation type occupying this area is seasonal dry forest, with endemic cacti species, similar to the Pai Vitório Fault unit due to the geomorphological and pedological similarities.

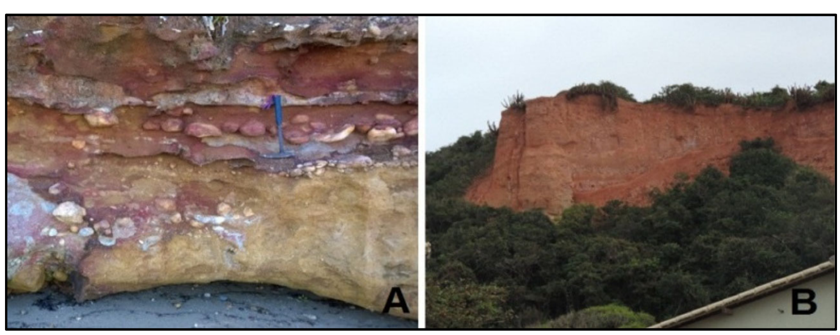

Fig. 12 **a** Conglomerate from the Barreiras Formation; **b** paleocliffs, which are inherited landforms from periods of marine transgression during the Quaternary

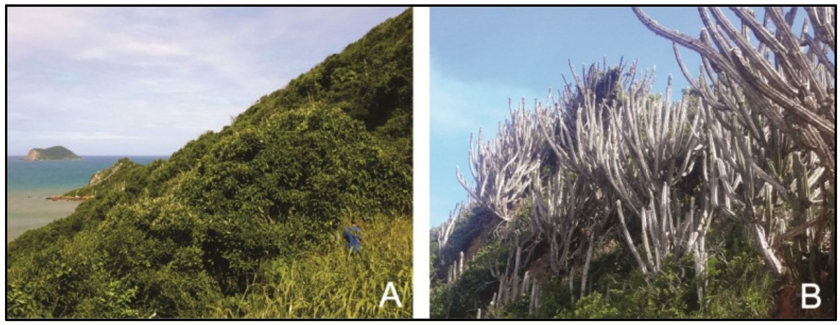

Fig. 13 **a** Hills aligned with the fault. It is interesting to observe that the island in the back is also aligned with the hills and the fault; **b** endemic cacti species

Rocky Shores

The rocky shores are environments between the coastal hills and the ocean, consisting of solid rock under the direct influence of waves, currents, and tides. The unit is subdivided into two subunits as a result of lithological differences, since it is mainly associated with the paragneisses of the Búzios unit (Fig. 15a), but also associated with the orthogneisses of the Região dos Lagos unit (Fig. 15b). In Fig. 15, it is possible to observe that the influence of the ocean prevents the development of any vegetation, which only occurs above the height that waves reach in the highest tides.

Linear Ridge

The Emerenças Linear Ridge is the most prominent relief form in the area, consisting of a crest developed along a thrust fault that separates the orthogneisses of the Região dos Lagos unit from the metasedimentary rocks of the Búzios unit. The high declivities, especially on the northern slopes, are the basic condition for the presence of shallow soils, predominantly red ultisols and cambisols. In Fig. 16, it is possible to observe the difference between the vegetation types due to topographical and pedological differences. Seasonal Dry Forests with cacti species occupy the steepest areas (Fig. 16a) while areas with more gentle slopes enable the development of semi-deciduous seasonal forests (Fig. 16b).

Gneisses Forming Low Hills with Gentle Slopes

This unit is mainly distributed over the continental portion of the municipality, in an area where the orthogneisses of the Região dos Lagos unit are highly chemically weathered (Fig. 17a) and the relief consists of hills with low declivities and wide summits, rarely reaching altitudes of more than 50 m (Fig. 17b). Deep yellow and red-yellow ultisols are predominant in this unit. However, similar morphologies occur on the peninsula, associated with the paragneisses of the Búzios Unit and yellow oxisols. This justifies the division into two subunits which are both occupied by semi-deciduous seasonal forests, which are shown in Fig. 17b.

Planed Surfaces

The planed surfaces are mainly distributed over the continental area, consisting of severely eroded areas, associated with highly chemically weathered orthogneisses overlain by haplic albaqualfs. Figure 18a shows the flat relief characteristics of the planed surfaces, without significant surface variations, and Fig. 18b shows a profile of haplic albaqualf, in which it is possible to observe the abrupt change in soil texture. Small enclaves of this unit occur on the peninsula, associated with paragneisses and overlying yellow oxisols. The predominant vegetation type is the semi-deciduous seasonal forests.

Discussion

The geodiversity map is the result of an integrated analysis of the physical environment. The association between geology, geomorphology, and soils is expressed in different ways throughout the territory and could be used to define potential advantages and limitations to the anthropic use of each

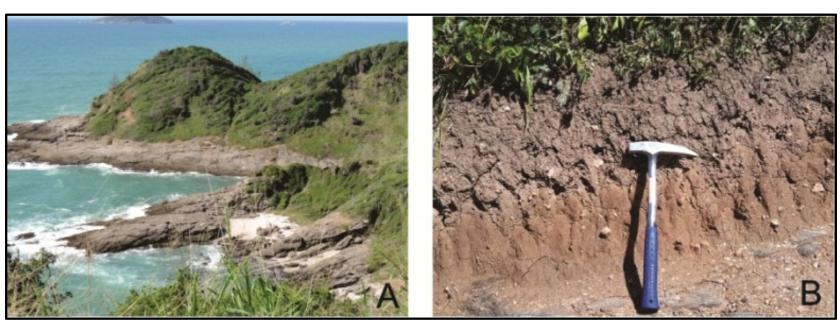

Fig. 14 **a** Hills with steep slopes and **b** chromic luvisol. The high declivities prevent the development of deep soils, creating conditions for the establishment of seasonal dry forests

Fig. 15 Rocky shores—**a** paragneisses at Foca Beach; **b** orthogneisses at Caravelas Beach. The direct influence of the ocean determines the main characteristics of this unit, composed of bare rock outcrops, with no development of vegetation

geodiversity unit, highlighting the application of this product in land management issues.

Each geodiversity unit was described according to the geological, geomorphological, and pedological settings. Hydrology was important for the definition of some units, such as beaches and rocky shores (where the influence of the ocean is the main factor), and the stone mangroves (which are characterized by the presence of underground water discharging in three specific points, creating conditions for development of the mangrove). The geodiversity map is therefore reflecting geodiversity as defined by Gray (2013).

The method to create the geodiversity map was based on the geodiversity maps developed by the CPRM albeit at a much more detailed scale. The geodiversity map is, therefore, a novelty since the small scale of the CPRM maps represents one of the main limitations for their implementation in land management.

One of the most important issues highlighted in studies of geodiversity mapping is the scale, especially when it is focused on the relationship with biodiversity (Hjort et al. 2012; Pellitero et al. 2014). The available data for the study area enabled only a landscape-scale analysis. The geomorphological map, scale 1:25,000, was used as a basis to create the geodiversity map, and it was correlated to the potential vegetation map, scale 1:30,000. The ideal situation would be to use maps at the same scale. However, as this is rarely feasible, the use of maps with similar scales is acceptable and the results achieved did not show significant discrepancies.

The inclusion of information on vegetation types on the geodiversity map showed a direct relationship, since the different conditions provided by each geodiversity unit determine the development of different vegetation types. Species diversity can be measured at different levels and scales (local, landscape, regional, and inter-regional, as described in Whittaker 1972; Whittaker et al. 2001). The available data did not enable an evaluation of the biodiversity, although by indicating that different plant communities occupy different physical settings, it shows that more geodiverse areas host greater habitat diversities, being in line with the findings of other authors (e.g., Barthlott et al. 2007; Jacková and Romportl 2008; Parks and Mulligan 2010).

The qualitative approach to geodiversity mapping showed that the Armação dos Búzios, despite its relatively small territory, presents significant spatial heterogeneity in terms of geological, geomorphological, and pedological elements. Since species tend to evolve occupying different niches and habitats (Whittaker 1972), this spatial diversity is also of temporal importance in the evolution of species. As concluded by Hunter Jr et al. (1988), landscapes encompassing a broad range of environments enable adaptation of organisms through time in response to environmental changes. Therefore, even though the species may not be the same, areas with high spatial heterogeneity will always be important due to their habitat diversity. As a result geodiversity must also be a target for long-term conservation efforts.

Hjort et al. (2015) presented the importance of taking the geological and geomorphological setting into account in the management of sites with special biota occurrences. Understanding the physical elements and relationships with biodiversity is crucial for developing effective management

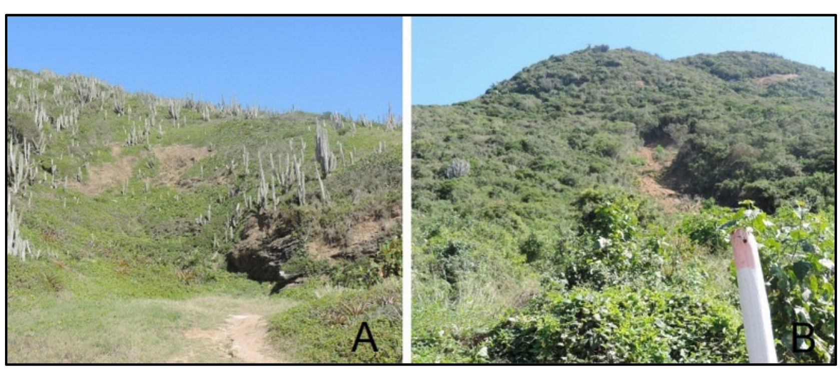

Fig. 16 **a** Emerenças linear ridge occupied by seasonal dry forests (also with cacti species) on the steepest slopes and **b** semi-deciduous seasonal forests occupying the less steep areas

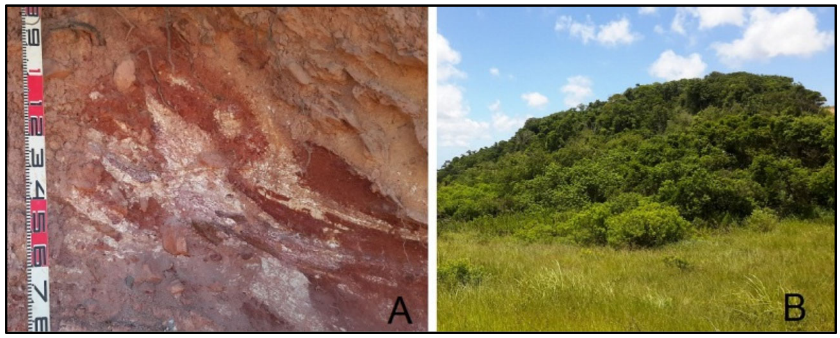

Fig. 17 The high degree of weathering and erosion of the orthogneisses (**a**) contributes to the relief forms of low hills with gentle slopes (**b**). These gentle slopes enable the development of deep soils, which in turn creates conditions for the establishment of semi-deciduous seasonal forests

of the sites in a context of environmental changes. Despite the differences in scale, the geodiversity map presented here is concerned with the same issues, since it presents an integrated setting of the physical environment. The positive correlation with vegetation types corroborates the importance of applying this product to territorial management, especially in nature conservation contexts.

The results achieved strengthen the idea that the use of geodiversity as a biodiversity indicator is valid and should be further explored. The lack of biodiversity data, especially in Brazil, has been a motivating factor in research investigating the power of surrogates, which could help fill these gaps. The concept of geodiversity has been growing in importance, especially during the last decade, and its potential application in biodiversity issues is one of the most important for the concept to be more widely used as whole.

Conclusion

The objective of this research was to create a geodiversity map and analyze how it would be linked to vegetation types on a regional scale. The methodology used consisted of an adaptation of the geodiversity mapping methodology developed by the Geological Survey of Brazil (CPRM), which was applied on a much more detailed scale. It therefore represents an innovative approach, consisting of an adaptation of the methodology to smaller areas, requiring more detailed information. Due to a lack of more specific data on biodiversity, the variations of vegetation types were used to represent the relationship between geodiversity and the biological environment, with the results showing a positive qualitative correspondence.

The municipality of Armação dos Búzios presents very interesting geodiversity, which is reflected by equally interesting biodiversity. However, especially as a result of tourism, the natural environment is under threat and the implementation of proper environmental management is of paramount importance. This kind of situation is common in Brazil due to its natural diversity and, at the same time, the lack of data and public policies taking into account an integrated approach to nature considering the importance of its conservation. Therefore, the improvement of geodiversity mapping methodologies is an important tool and it is expected that this research provides an incentive to similar applications in other areas.

The current global environmental problems and questions demand new scientific perspectives and the improvement of paradigms and methodologies. The use of geodiversity, by describing the substrate in which biological and human activities take place, is of paramount importance and must have its potential explored. The results achieved here endorse the importance of geodiversity mapping in understanding vegetation distribution patterns, reaffirming the potential for application within nature conservation issues as a land planning and management tool. The geosciences have a key role within nature conservation and geodiversity must achieve the same level of importance as biodiversity, strengthening the holistic approach to nature and helping in the creation of a new paradigm in the relationships between nature and society.

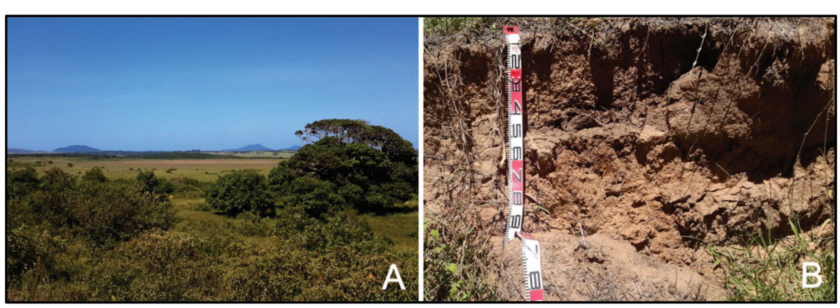

Fig. 18 **a** Planed surfaces occupied by semi-deciduous seasonal forests and **b** haplic albaqualfs, which are the main soil types of this unit

Acknowledgements This work was funded by the National Council for Scientific and Technological Development and strongly supported by the Geological Survey of Brazil (CPRM). We would like to express our gratitude to Prof. Dr. José Carlos Sícoli Seoane, Prof. Dr. Renato Cabral Ramos, Prof[a]. Dr[a]. Úrsula Ruchkys de Azevedo, and two anonymous reviewers that contributed significantly for the improvement of this article.

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