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ORIGINAL ARTICLE

Ecosystem Services Provided by Geodiversity: Preliminary Assessment and Perspectives for the Sustainable Use of Natural Resources in the Coastal Region of the State of São Paulo, Southeastern Brazil

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Abstract
Geodiversity-based ecosystem services are functions provided by elements of geodiversity that benefit society and future generations. Their adequate evaluation is important to assess losses and the value of nature, both qualitatively and quantitatively, and may be the key to the sustainable use of natural abiotic heritage by means of inclusion in land-management programmes. This work first presents an initial contribution to the inclusion of geodiversity in the ecosystem approach in the coastal region of the state of São Paulo, Brazil. The qualitative evaluation presented has identified 56 ecosystem services distributed across four functions—regulation, supporting, provisioning and cultural—that give an overview of the importance of geodiversity in the region. The ecosystem approach is placed as a potentially important influence on public policies for the management of geodiversity and geoheritage, depending on the effectiveness of communication with decision-makers and society. It is also the intention to provide the bases for future works regarding the detailed assessment of ecosystem services in the context of geodiversity in the region.

Keywords Ecosystem services · Geodiversity · Geoheritage · Public policies · Serra do Mar

Introduction

Geodiversity-based ecosystem services are defined as functions provided by elements of geodiversity, either directly or indirectly, for the benefit of the society and future generations (Gray 2013). The ecosystem approach has been widely used in the analysis of the services that society obtains from the natural environment, in an attempt to assess both quantitatively and qualitatively the value of nature (e.g. Costanza et al. 1997; Alcamo et al. 2003; Fisher et al. 2009). Preston and Raudsepp-Hearne (2017) pointed out that ecosystem service assessments can support analyses and decisions in five broad groups of policy issues: area-based planning, regulatory decision analyses, environmental damages assessment, environmental management and conservation instruments.

Traditional approaches include only services associated with processes and interactions between the biotic and abiotic environments, excluding purely abiotic services and prejudicing a complete assessment of the natural environment in focus (Gray 2018). Since geodiversity is part of the natural environment, the evaluation of ecosystem services must consider geodiversity elements not only as part of ecosystems, but also as individual entities with particular properties, such as sedimentary layers or magmatic intrusions. The main focus of the ecosystem service approach to geodiversity is therefore on finding a broad way of treating the natural environment in a sustainable way, considering the management of land, water and living beings, which is a reflection of society's aspirations and climate change (Gordon et al. 2012; Hjort et al. 2015). Likewise, associations between geodiversity and biodiversity must be properly understood as the basis for developing responses to current issues, such as the pressure on supplies of natural resources and climate change (Prosser et al. 2010; Brazier et al. 2012).

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The ecosystem services provided by geodiversity are grouped according to four functions, regulation, provisioning, supporting and cultural (Gray 2013; Brilha et al. 2018), and their adequate evaluation may be the key to the sustainable use of natural abiotic heritage by means of inclusion in land-management programmes.

The area studied in this work—the coastal region of the state of São Paulo, Brazil—is a traditional tourism destination. Its ecosystems play an important role in providing goods and services to the population, but being located in the most populated and industrialised state of Brazil, the region is the focus of extreme real-estate speculation and a tourism industry that lacks environmental concerns, endangering both the quantity and the quality of these services (Garcia et al. 2018a).

In this context, as an initial contribution to an abiotic part of the ecosystem approach, a preliminary inventory of the contribution of geodiversity for the ecosystem services in the region is presented, both to guide future territorial planning and to promote a better use of geodiversity resources.

The Study Area

The coast of the state of São Paulo (Fig. 1) has been the focus of geological site inventories for geoheritage purposes since 2012. Around 130 sites have already been selected, providing the basis for several initiatives both to disseminate geological knowledge and to raise awareness of geoheritage in society (Garcia et al. 2017; Garcia et al. 2019). The present physical configuration of the region is a result of geological, geomorphological and climate processes acting since the Archaean, including the amalgamation of West Gondwana Supercontinent (Neoproterozoic), the opening of South Atlantic Ocean (Jurassic–Cretaceous), the formation of the Serra do Mar Mountain Range (Upper Cretaceous–Paleogene) and variations of sea level (Quaternary). All these processes acting heterogeneously caused strong differences in the morphodynamical nature along the whole coastal zone, controlling the assessment and management of geoheritage.

According to its geomorphological characteristics, the region may be divided into distinct segments (Souza 2012). The northern segment is characterised by a highly indented coastline with small drainage basins, bays and beaches separated by rocky promontories, as well as numerous islands. The Serra do Mar slopes are close to the coastline. In the Central segment, a tectonic-related estuary complex with tidal channels and mangroves had a major controlling influence of human occupation and land use. The local history has strong links with the colonisation of the country in the sixteenth century, and the first Brazilian village, São Vicente, is located in this segment. Being closest to the state capital, São Paulo, and holding the biggest port in the country, Santos, the rapid growth of the population and the urbanisation are critical issues that affect the area. Most of the natural heritage has been destroyed, but partly can be seen in several historical monuments and buildings. Towards the south, where mainly dissipative, long beaches predominate, the coastal plains are large, and the Serra do Mar is dozens of kilometres away from the coastline. A large estuarine lagoon system associated with the largest watershed on the coast, the Ribeira do Iguape River, is the main local feature. Active erosion processes are frequently enhanced by human activities, making the sites extremely vulnerable and fragile (Garcia 2017).

Besides its geodiversity value, the region comprises a number of protected areas, including two UNESCO Biosphere Reserves related to the Atlantic Forest. It is also home to important traditional communities, such as fishermen (the Caiçaras), inhabitants

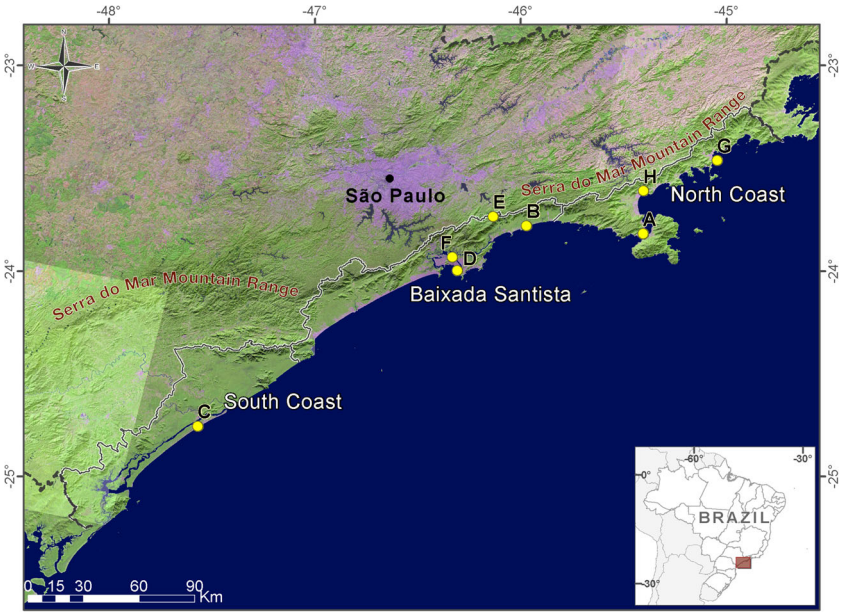

Fig. 1 Location of the study area showing the limits of the segments that form the coastal region of the state of São Paulo, Brazil. The letters A–H correspond to the places shown in Fig. 2. The insert shows the limits of the main image on the map of Brazil (red rectangle). Mosaic of Landsat RGB753 images of different dates, which may result in textural/colour differences

of the remnants of former African slave settlements (the Quilombolas) and indigenous people (mainly Guarani and Mbya-Guarani ethnic groups), which have outstanding intangible cultural heritages. Strong relationships between built heritage and geodiversity are extensively found in stone materials used in constructions and monuments.

Methodology

The methods used in the identification and evaluation of ecosystem services vary according to the approach and the purpose of the work, and can range from qualitative methods, including consultation with key social players, and matrix approaches with the resulting maps, to quantitative methods, which involve monetary valuations. In this work, the preliminary inventory of how geodiversity contributes to ecosystem services was carried out according to the following steps, which were adapted from the guidelines of Everard and Waters (2013) and Preston and Raudsepp-Hearne (2017).

1. Definition of the ecosystems—The broad ecosystem types were identified through specialised references. Both terrestrial and aquatic, as well as transitional, ecosystems were considered. In the area studied, the ecosystems are mostly typical of coastal regions and are generally associated with the Atlantic Forest, which is located along the Serra do Mar Mountain Range. From the Serra do Mar to the ocean floor, ecosystems range from continental, essentially terrestrial, to aquatic–fluvial, coastal and marine. In general, the boundary between these ecosystems is quite tenuous and varies according to the degree of interaction between them. The definition of the ecosystems was based on the work of Prates et al. (2012);
2. Qualitative characterisation of geodiversity (abiotic) elements—Correlation of geological materials (lithologic types, sediments, soils, etc.), structures (shear zones, faults) and relief forms (slopes, valleys), among other components of the physical environment, as components of each ecosystem (Table 1). The geological processes are also considered as part of these ecosystems;
3. Identification of ecosystem services—The ecosystem services of geodiversity proposed in Gray (2013) and updated in Brilha et al. (2018) were evaluated according to their involvement in each previously defined ecosystem.

Results

Regulating Services

In this region, many regulating functions are associated with mangroves, in which the rates of accumulation of allochthonous and autochthonous sediments may vary greatly depending on sedimentation conditions. This includes the capacity to recharge aquifers, flood control, stabilisation of the coastline through erosion control, sediment retention, pollutants and solid-waste regulation, storm and wind protection and stabilisation of some microclimates. Studies of the valuation of the ecosystem services of mangroves have indicated the great dependence of the fishing communities and tested the perception of tourists by using the "travel-expenses" technique (Grasso 1994; Tognella 1995). In the Araçá Mangrove, São Sebastião, Turra et al. (2017) list services such as water purification related to the processing of atmospheric carbon by the local hydrodynamics and organisms, in addition to the supply of food for the fauna (Fig. 2a).

River ecosystems encompass both river channels and flood plains. They constitute transitional environments, in which water and sediments loaded by rivers are transported and deposited in the plains, causing the soil to become quite rich. In this area, regulation services associated with river basins, such as local and global climate regulation, protection of oceanic coastline, prevention of landslides, flood and flood prevention were identified (Buchianeri 2017). These areas are also responsible for the filtration of nutrients and sediments of rivers, acting as reservoirs, regulating the volume of water and promoting its purification.

According to Souza (2012), the current coastline of the state of São Paulo has around 430 km of sandy beaches. Together with dunes, they act as a coastal defence, helping to attenuate the energy of waves and storms, with a consequent reduction of damage. The beaches also promote the filtering of large volumes of water and actively participate in the cycling of nutrients (Barbier et al. 2011).

Several studies have demonstrated the influence of the Serra do Mar topography on rainfall indices in the coastal plains, showing a clear relationship between greater rainfall averages and consequent rainfall erosivity, and the orographic effect of the mountains (Terassi and Galvani 2017). The combination of the NE–SW orientation of the Serra do Mar with the humid winds from the ocean acts as an intensifier of this orographic effect (Pellegati and Galvani 2010) (Fig. 2b).

In addition, marine sediments are powerful containers for stocks, acting as regulators of climate change and greenhouse gases (Nellemann et al. 2009; Avelar et al. 2017).

Supporting Services

One of the most significant influences of geodiversity is the relationship between the rocky substratum and the vegetation cover. In this area, the soil formed by granitic-gneiss rocks that make up the Serra do Mar supports one of the largest Brazilian biomes, the Atlantic Forest, which covers around 13% of the Brazilian territory (IBGE 2018). Towards the coast, the deposits become sandy and pelitic, the slope decreases greatly, especially in the lowlands, and the size and the type of the vegetation also changes, from dense ombrophilous forest to low dune and beach plants (Souza and Luna 2008) (Fig. 2c).

Table 1 Characteristics and elements of geodiversity associated with continental, coastal and marine ecosystems of the coast of São Paulo. Values in parentheses refer to the approximate areas of each ecosystem (in ha). Data sources: Perrotta et al. (2005), Chang et al. (2008), Souza (2012), Prates et al. (2012), Riccomini et al. (2012)

• Ecosystem	• Features and limits	• Elements of geodiversity
South Brazil Shelf[1]	Includes the shelf, the shelf-slope front and part of the slope along the segment called the Southeastern Bight (23–28° S)	Sedimentary rocks of the Santos coastal basin, acting as reservoirs and sealants, as well as structures such as faults and folds that serve as traps for oil and gas, including extensive pre-salt deposits Coastal sand deposits Marine relief features Santos Fault
Rocky shore (38,000)	Igneous and/or metamorphic rocks occurring in the transition with the sea. These may be outcrops or concentrations of blocks	Precambrian igneous and metamorphic rocks Basaltic, lamprophyric and alkaline dykes Syenites
Beach (4000)	Region of accumulation of sandy sediments from the degradation of mainly Precambrian rocks and transported by rivers originating in the plateaux	Sandbars, tombolos, barrier beaches, barrier islands
Dune (0.2)	Accumulations of sand formed by wind processes. They may or may not have vegetation. Restricted to the southern segment	Quaternary sand sediments Coastal dunes Paleodunes
Mangrove (25,000)	Transition zones between fluvial and marine environments	Laminated fine-grained sediments Fluvio-marine sedimentary processes
Estuary and lagoon (23,000)	Includes the mouth of rivers in which the channel is invaded by seawater and flooded areas	River channels Alluvial plains Deltas
Coastal plain[2] (115,000)	Sand deposits made up of plain and coastal strands	Sandy soil Old and modern marine terraces and plains Coastal plains Marine sand deposits
River (900,000)[3]	Includes the river channels formed from the Precambrian basement to the coastal plains and adjacent areas	River channels Alluvial plains Sandbars Valleys Fluvial sediments Channel deposits
Serra do Mar	Corresponds to steep slopes down towards the ocean and the plateau portion	Ortho- and paraderivate Precambrian gneisses Granitic rocks Shear zones and faults Soils Mountain relief

[1] Based on the Large Marine Ecosystems (LME) (Sherman and Alexander 1986; see also www.st.nmfs.noaa.gov/ecosystems/lme

[2] In the ecology literature, these coastal ecosystems, as well as coastal plain and mid-slope vegetations, are often designated as *restinga.* However, this term had long been used in a geological connotation for many types of coastal sand deposits (Souza et al. 2009) and for this reason, in this work the term *restinga* is avoided to refer to a specific type of ecosystem

[3] Sum of the drainage areas of the main river basins (SigRH 2019)

Coelho et al. (2010) identified that the relief and the oscillations of the level of the water table are the main factors that condition the distribution of spodosols in the sea terraces, which reinforces the close relationship between soil formation and geomorphological features. The types of hillside soils, with a sandy-clay composition and rich in organic matter, are preferred for banana growth, and it is not by chance that the state of São Paulo is a major producer of the fruit (Menezes and Galvão 2004).

Geodiversity plays an important role in the conservation of biodiversity by providing habitats and nurseries for a large number of terrestrial and marine organisms, as well as birds. The rocky shores consist essentially of two types of rock sets: Precambrian granite-gneiss terrains, related to the former Gondwana Supercontinent, and both basaltic and alkaline volcanic rocks, associated with post-breakup magmatism (Bacci et al. 2019). These rocky shores can be good biological and geomorphological indicators of sea-level variation and may establish relationships between geodiversity and biodiversity, such as the hedgehog bands studied by Teles (2016).

Mucivuna et al. (2016), in a study about the fortifications on the coast of São Paulo, reported the use of rock platforms for

Fig. 2 Ecosystem services provided by geodiversity in the coastal region of São Paulo State, Brazil. Regulation services: (a) Araçá Mangrove, São Sebastião, currently under threat from a project to enlarge the local port. To the left is part of geosite "Dykes of Ponta do Araçá", a geosite that holds the registers of important magmatic events related to the breakup of West Gondwana; (b) view of the geosite "Pleistocene terraces of Itaguaré Beach" (at the centre of the picture), in Bertioga. In the background, we see the Serra do Mar Mountain Range escarpments, the relief of which has a significative influence on the average rainfall in the region. Supporting services: (c) geosite "Sand dunes of Ilha Comprida", showing arbustive vegetation typical of these features, which also provide an area for migrating birds to rest and feed; (d) Santo Amaro da Barra Grande Fortress, Guarujá, built in 1854 on a porphyritic granite-biotite platform (Mucivuna et al. 2016). Provisioning services: (e) water catchment in the Itatinga River, Bertioga, located in the middle of the Atlantic Forest. The river originates from the high plateaux of the Serra do Mar Mountain Range and supplies a hydroelectric plant that provides energy for the Port of Santos, the biggest port in Brazil; (f) Outeiro de Santa Catarina, in Santos. It is considered the initial mark of the town, being the whole set composed of outcrops and blocks of mylonitic gneiss and the house built on the remains of a former sixteenth-century chapel. The columns and the ground are made up of gneiss, which has been partially extracted for using in the pavement of the streets (Queiróz et al. 2019). Photo: L. Dehira. Cultural services: (g) Geosite "Mantle xenoliths of Vermelha do Centro Beach", which is used for educational purposes for Igneous Petrology as part of the Geology bachelor's course at the University of São Paulo; (h) interpretive panel at the Santo Antonio viewpoint, Caraguatatuba. The panel tells the geological history of the formation of the Serra do Mar Mountain Range. English versions of all the panels can be found at www.igc.usp.br/geohereditas

constructions (Fig. 2d). Examples of the use of geodiversity by ancient peoples can be found in Ilhabela, on the northeast, such as the use of rock cavities as natural shelters (Bendazzoli et al. 2009). Substrate and underwater forms support a wide variety of marine habitats and species, often defined by elements of geodiversity, such as caves and small recesses.

Provisioning Services

The ecosystems of the coast of São Paulo are responsible for providing goods and services that are essential both for the survival of local communities and for the economy and culture of the region. Perhaps the most important provision service provided by geodiversity in the region is drinking water. Unlike the plateau region, where the state capital is located and where the water supply is mainly supplied by dams, water in the coastal region is captured at specific points of rivers from the Serra do Mar water-supply systems, the high altitudes of which increase the incidence of rainfall, favouring water availability (Fig. 2e).

Geodiversity materials have been used since colonial times in the construction of buildings for various purposes. Among these are the large numbers of buildings along the central coast, where the geological heritage has been drastically destroyed due to the great degree of urbanisation (Fig. 2f)—detailed information in Mucivuna et al. (2016) and Arruda et al. (2017). One of the best-known stone products is Green Ubatuba Granite, the extraction of which was prohibited in 1977 due to the creation of the Serra do Mar State Park, which constitutes several monuments in the old town of São Paulo (Del Lama et al. 2014). Exploitation of residual soil (*saibro*), originating from the alteration of granite-gneiss rocks, occurs especially in the northeast (Ferreira and Fernandes da Silva 2008). Clay has always played an important role in the process of urbanisation of the region, since it was widely used for foundations in flooded areas, permitting the installation of residential nuclei and the creation of road networks. The extraction of sand also constitutes an important activity.

In terms of mineral economic resources, oil and natural gas in the sedimentary rocks of the Santos Basin—the largest offshore sedimentary basin in Brazil—are the most important. The state of São Paulo is the second-largest oil producer in Brazil (469 thousand barrels of oil/day) and the second-largest producer of natural gas (19 million cubic meters/day) (CEPE 2012. The continental shelf and adjacent marine areas also hold a number of mineral resources, such as heavy minerals on the southwest and bioclastic granulates on the northeast that can be exploited over the so-called Exclusive–Economic Zone (EEZ) (Souza 2008; Cavalcanti 2011).

Cultural Services

The coast of São Paulo exhibits scenic beauties that are widely exploited by tourism. Associated with tropical climate, beaches, waterfalls and the Serra do Mar escarpments, it provides rest and recreation for thousands of visitors and residents. In addition, these natural features, dominated by the Serra do Mar and the ocean, are directly related to cultural aspects of the region.

Geological heritage is an indisputable part of the natural capital of the region, since it includes sites that allow geoscientists to unravel the geological history and to understand and to predict current and future processes. Since 2012, the region has been the focus of inventories of sites of geological interest, which are strongly based on scientific investigations in several areas of knowledge related to geosciences. These studies are important due to the information they can provide about the history of the landscape—including the formation of the South Atlantic Ocean, records on past climate changes in sedimentary rock sequences and in sediments—and for evaluating the economic resources in the Brazilian continental shelf, as well as providing information on the evolution of ecosystems, how they change over time and their outlook for the future. Several subjects in geoscience-related undergraduate courses use outcrops and coastal landscapes for field classes (Fig. 2g), including the Coastal Ecosystems Project (Berchez et al. 2005) and an educational kit using samples of beach sands, rocks and materials (Bourotte et al. 2014).

Many of these sites are of major touristic or educational significance and are related to numerous legends and folk stories (see Garcia et al. 2019 and references therein) and have been the focus of geotouristic initiatives, such as interpretive panels (Fig. 2h), and provided artistic inspiration since colonial times, for works such as the paintings of Jean-Baptiste Debret (1768–1848) and Benedito Calixto (1853–1927). The region has one of the largest sets of protected areas in the state, which although created with a focus on biodiversity make notable use of elements of geodiversity for recreation and well-being, as pointed out by Jericó-Daminello (2014) in the Marujá community, in the south. Examples are ecotouristic trails, which constitute effective ways to enhance both the experience of nature and the dissemination of geoscience.

Table 2 shows a synthesis of the main ecosystem services inventoried in this work, which were identified according to ecosystem type and related elements of geodiversity.

Discussion

Impacts on geodiversity are largely related to pressure for economic development and to changes in land-use patterns, which can affect the elements of geodiversity in many ways. Since geodiversity concerns the abiotic component of ecosystems, these impacts can result in severe losses in the supply of goods and services provided by these environments. From the Serra do Mar to the marine environment, the coastal region of São Paulo is made up of fragile ecosystems that are often affected by both natural processes and human activities. These distinct ecosystems are affected to various degrees by threats such as real-estate speculation, constructions that modify natural coastal dynamics, unplanned exploitation of sand, grit and residual soil for fill, deforestation, mass tourism,

Table 2 Goods and services provided by geodiversity in the coastal region of the state of São Paulo, Brazil

Ecosystem	Regulation	Supporting	Provisioning	Cultural
South Brazil Shelf	• Oceanic circulation promoted by marine landforms • Global climate regulation and carbon storage by marine sediments	• Participation in water cycling • Habitat provision for both animal and vegetal species	• Food supply by providing habitats for edible sea species • Oil and gas supplies	• Scientific research into several branches of geosciences • Educational value as field resources for geoscience students
Rocky shore	• Chemical weathering of silicate rocks regulates the long-term carbon cycle	• Habitat provision • Places for anchorage • Foundations for human constructions • Shelters for ancient settlements	• Natural and cultivated food production	• Research centres on coastal and marine topics • Recreation and tourism in coastal islands, rocky shores, beaches, trails, waterfalls
Dune	• Importance in water infiltration and the recharging of aquifers, and as part of the hydrological cycle • Control of water quality	• Control and storage of water	• Habitats for specific plant species	• Sense of place and spiritual values, especially for traditional communities. • Promotion of voluntary work on nature conservation
Mangrove	• Storage of blue carbon • Control and storage of water • Wave-energy dissipation	• Participation in water cycling • Habitats for different life forms	• Terrestrial or transitional shelter or nursery • Natural and cultivated food production	• Studies of long-term processes • Health and well-being promoted by scenic beauties
Beach	• Erosion control • Wave-energy dissipation and shoreline protection	• Natural retention and sediment transport • Water filtration	• Fishing	• Protected areas controlled by the occurrence of the Serra do Mar, estuaries, lagoons and islands • Records of past climates
Estuary and lagoon	• Natural hazard regulation by erosion control	• Participation in water cycling	• Refuge and/or marine nursery • Natural and cultivated food production	• Dissemination of geosciences by interpretive panels, didactic kits, courses and guided trails
Coastal plain	• Erosion control • Recharge of aquifers	• Typical *restinga* vegetation	• Terrestrial or transitional refuge or nursery	
River	• Water flow and flood regulation • Draining • Participation in water cycling and ocean circulation	• Participation in water cycling • Water pathways for transportation	• Water supply by several river basins with sources in the Serra do Mar and in the Atlantic Plateau • Sand exploitation • Energy supply from hydroelectric plants	
Serra do Mar	• Local climate regulation by the Serra do Mar Mountain Range	• Soil formation as support to the Atlantic Forest vegetation and to the banana cultivation	• Rocks, saprolite and sands as ornamental and construction materials	

unplanned human occupation, exploitation of hydrocarbons, gas pipelines, navigation, pollution, coastal erosion, waste disposal and military activity. Besides local consequences, these activities can affect distant regions, depending on the dynamics of the political and economic systems involved. Therefore, in addition to the identification of impacts and threats to geodiversity, it is also necessary to evaluate the risk of degradation of the elements involved in terms of both fragility and vulnerability, so that the results may be used in the management of the natural environment.

Nature-conservation policies have been implemented mainly through the creation of protected areas, generally concerning biodiversity. However, as previously mentioned, geodiversity provides the substrates, relief forms and dynamic processes required for the development and maintenance of habitats for animal and plant species. Therefore, the implementation of a strategy that values the protagonism of geodiversity in nature is essential to long-term nature conservation, as well as the ecosystem services provided by this abiotic part of nature.

Much of the coast of the state of São Paulo—especially the northeastern and central parts—is the focus of extreme real-estate speculation, causing many areas to become the target of tricks to try to bypass the legislation. In some municipalities, the occupation of the coastline has been responsible for marine terraces, estuary areas and lagoons and mangroves becoming impermeable, causing changes in the drainage pattern in the region. Accelerated urbanisation has been causing the loss of a great deal of geodiversity, as attested in the paper by Queiróz and Garcia (2017). It is not uncommon to find places where urban growth occurs in the backshore zone, directly affecting the sedimentary balance of the beach. Changes in the coastal geography caused by anthropic interventions that modify the natural dynamics may reach historical proportions. In the southwest, the opening of the Valo Grande canal in 1855 has been causing major changes in both the course and location of the estuary of the Ribeira de Iguape River, as well as in the coastal dynamics and sand supply. Also, one of the most urgent threats and a potential direct damage to geological heritage is the recently approved Ecological–Economic Zoning (EEZ) plan for the northeastern coast, which has significantly changed the granting of permission for the expansion of industrial and port areas. It allows the construction of industrial complexes, gas pipelines and thermoelectric power plants in the Caraguatatuba coastal plain, which is host to geosites with rare records of sedimentary features related to episodes of marine transgression and regression. Other important records of the Pleistocene sedimentation associated with the Cananeia transgression in the region, described by Souza (1992), have been already destroyed due to unplanned urbanisation, which has led to the often unregulated occupation of river banks, longitudinal beach deposits, mangroves and dunes. In this sense, tourism, although a fundamental economic activity for most of these coastal counties, has a negative effect felt through the pressure exerted on the beaches, the movement of vehicles and trampling of structures, especially in coastal and supra-coastal areas.

In this sense, the adequate study of geodiversity and geological heritage can make important contributions to the identification of potential areas for protection. An example of the importance of these studies is the recognition of coastal geosites, defined in Garcia et al. (2018b), as special areas in the Management Plan of the Marine Environmental Protected Areas in the state of São Paulo.

The prediction of environmental impacts can also be substantially enhanced with the use of the ecosystem approach, considering the processes and the ecosystem services affected. Furthermore, this can be the key to raising awareness of the losses due to the degradation of the natural environment and the need for protection. At the same time, the conservation of nature as a whole and all its benefits require the appropriate participation of decision-makers and managers, as well as of society. The ecosystem approach has the potential to highlight the issues arising from the loss of goods and services caused by the degradation of the abiotic environment and can contribute to initiating a broad discussion in this respect. Confronting potential scenarios in which the decline of ecosystems would bring about irreparable damage to the modern way of life can make society aware of its role in dealing with environmental issues.

The adequate recognition, cartography and characterisation of the ecosystems are tasks that should be carried out in association with other specialists, such as biologists and ecologists. Better integration of geodiversity and biodiversity as part of the science of geosystems is critical for the future of ecosystems and their services, and provides opportunities and challenges for applied geoscience. This reinforces the need for a broad strategy that involves nature conservation as a whole.

The ecosystem approach can influence public policies on the management of geodiversity and geoheritage, in the sense that it can demonstrate the relevance of these services and how the loss of natural value affects them. Even though it may be obvious to geoscientists that geodiversity is associated with essential services for society, this information is not always effectively communicated to decision-makers. The language and mode of dissemination of scientific information are largely ineffective in reaching society, and furthermore, they are insufficient to sensitise the state to the importance of conserving geodiversity.

Conclusions and perspectives

This survey is a primary contribution to the inclusion of geodiversity in the ecosystem approach in the coastal region of the state of São Paulo, Brazil. The qualitative evaluation

presented in this work has identified 56 ecosystem services distributed across four functions that provide an overview of the importance of geodiversity in the region.

Investigations into geological heritage and sites of geological interest that have been conducted in the region since 2012 have been providing solid data regarding the potential of these places for scientific, touristic or educational purposes, among others. Together with the assessment of ecosystem services, this information will permit future diagnoses regarding geoconservation in each specific subregion or municipality, detecting weaknesses and gaps and designing solutions. In practical terms, with these data, it will be possible to identify sites for priority management and use. Depending on the scale considered, different management proposals may be developed for a set of sites or for a specific site. The results obtained will therefore have the potential to constitute the basis for a strategy that may include participatory methodologies in the formulation of public policies aimed at social welfare and the search for solutions to current environmental issues. It should be emphasised that a strategy involving geodiversity management must encompass different stakeholders, in addition to geoscientists, and constitutes a valuable opportunity to interact with different sectors of society in the pursuit of common goals. More holistically, it is necessary for geoscientists to become aware of their social role and to establish partnerships with other fields, seeking new ways of communicating the benefits that geodiversity provides to science and society. In this sense, the information presented contributes to the understanding of the role of geodiversity in the coast of São Paulo and to the planning of long-term actions.

This work aims to obtain general information on the role of the abiotic portion of the ecosystems in the supply of numerous basic services. It also aims to provide a basis for future works regarding both the methodology for inventorying and assessing ecosystem services in the context of geodiversity and quantitative approaches that may include the payment for environmental services in the region.

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