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Quantitative assessment of geodiversity and urban growth impacts in Armação dos Búzios, Rio de Janeiro, Brazil

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ABSTRACT

The concept of geodiversity, which refers to the diversity of abiotic elements of nature, is passing through a period of methodological development. The concept has a great potential of becoming an efficient territorial management tool as the physical environment is the basis in which biodiversity and human societies develop. However, this potential has not yet been achieved because the methodologies of practical application are not consistent enough. This work aimed to contribute to this issue by applying a method of quantitative mapping of geodiversity at a landscape scale and integrating it to an urban growth map in Armação dos Búzios municipality, located in Rio de Janeiro State, Brazil. On the basis of some of the most important previous proposals, a Geodiversity Index Map of Armação dos Búzios was created, which shows the richness and distribution of the elements of geodiversity (geology, geomorphology, soils, and hydrology) throughout the territory. With this product, it was possible to identify the most geodiverse areas of the municipality. After that, an Urban Growth Map of Armação dos Búzios was created by the photointerpretation of aerial photographs from 1976 to 2006, in which the urban areas in both dates were mapped, allowing the observation of how much the urban area grew during this time. By integrating these two maps, we were able to quantify the impacted areas in relation to the geodiversity. The results showed that urbanization impacted a significant portion of the areas classified with high and very high geodiversity indices, highlighting that the physical environment, and consequently the biodiversity, are under serious threat, and it must be taken into account in public policies and territorial management. In addition, this work aimed to contribute to the methodological development of the concept of geodiversity, which still needs more tests and discussions to be improved and widely applied, especially in nature conservation issues.

1. Introduction

The concept of geodiversity is very recent and is passing through a period of consolidation. According to Gray (2013), the term is being used by geologists and geomorphologists since the 1990s to describe the variety of elements of the abiotic nature. The literature shows many definitions of the concept (Australian Heritage Comission, 2002; Eberhard, 1997; Gray, 2013; Nieto, 2001; Rojas López, 2005; Serrano & Ruiz-Flaño, 2007; Sharples, 1995). Although there are some points of disagreement between these definitions, it is important to emphasize that there is significant advancement on the theoretical definition of the term, which, however, has not been accompanied by an advancement in the assessment methods, so the concept became somewhat meaningless (Carcavilla, Durán, & López-Martinez, 2008, pp. 1299–1303; Pellitero, Manosso, & Serrano, 2014).

One of the first definitions of geodiversity is presented by Sharples (1995), in which geodiversity is "*the range (or diversity) of geological (bedrock), geomorphological (landforms) and soil features, assemblages, systems and processes.*" The Australian Heritage Comission (2002) complemented this definition by including that "*Geodiversity includes evidence of the past life, ecosystems and environments in the history of the Earth as well as a range of atmospheric,*

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hydrological and biological processes currently acting on rocks, landforms and soils."

Kozlowski (2004) defines geodiversity as "*the natural variety of the Earth's surface, referring to geological and geomorphological aspects, soils and surface waters as well as to other systems created as a result of both natural (endogenic and exogenic) processes and human activity.*" It is an integrative perspective, embracing geology, geomorphology, soils, and waters, as well as the associated physical processes. However, it includes human activity as capable of generating elements of geodiversity, which, as highlighted in Carcavilla et al. (2008, pp. 1299–1303), brings conceptual and, especially, practical problems.

Gray (2013) gives one of the most accepted definitions: *"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."* Similar to Kozlowski et al.'s (2004) definition, it is very integrative but restricted to the natural variety, which makes it easier to comprehend and apply in a practical approach. The author also highlights that many human activities threaten geodiversity, so it is important to use the concept in a nature conservation perspective.

The Geological Survey of Brazil (CPRM – from Portuguese *Companhia de Pesquisa de Recursos Minerais*), on the basis of some of the main definitions proposed so far, defines geodiversity as the study of the abiotic elements in nature (physical environment) consisting of a variety of environments, compositions, phenomena, and geological processes, which give rise to landscapes, rocks, minerals, waters, fossils, soil, climate, and other surface deposits, providing conditions for the development of life on the Earth and having the cultural, aesthetic, economic, scientific, educative, and touristic values as intrinsic values (Silva, 2008). It is an interesting definition for highlighting the importance of geodiversity as the substrate in which the biodiversity develops and for the inclusion of the values it has for human societies.

In a broad concept, natural diversity is the combination of biological and physical elements of nature. Therefore, geodiversity can be seen as complementary to biodiversity and not as a separate and unassociated approach (Crofts, 2014). Moreover, there is an understanding that a variety of landscapes would lead to an increase in habitat richness (Dufour, Gadallah, Wagner, Guisan, & Buttler, 2006; Jacková & Romportl, 2008).

Several authors recognize geodiversity as responsible for providing conditions for the development of biodiversity (Gray, 2013; Gray, Gordon, & Brown, 2013; Hjort, Heikkinen, & Luoto, 2012; Parks & Mulligan, 2010; Santucci, 2005). At the same time, there has been an increase in the concern for biodiversity conservation, especially in the context of current global change (Barnosky et al., 2011; Brooks et al., 2006; Dawson, Jackson, House, Prentice, & Mace, 2011). Geodiversity can add new dimensions to conservation planning because of its functional value that is related to the biodiversity (Anderson et al., 2015). However, despite the intrinsic relationship between biodiversity and geodiversity, the first is widely disseminated, while the latter is frequently referred to as a theoretical approach with no particular relevance or application (Pellitero et al., 2014; Pereira, Pereira, Brilha, & Santos, 2013).

Gray (2013) endorses the potential of geodiversity to become an efficient land-use planning tool, emphasizing the importance of the physical elements of nature. This potential has not yet been achieved, however, because the application methodologies are not consistent enough. Several authors from different parts of the world have proposed methods of geodiversity assessment, so the concept is undergoing a consolidation process of paramount importance (Benito-Calvo, Pérez-González, Magri, & Meza, 2009; Bruschi, 2007, p. 263; Hjort & Luoto, 2010; Kozlowski, 2004; Manosso, 2012, p. 183; Parks & Mulligan, 2010; Pellitero, González-Amuchastegui, Ruiz-Flaño, & Serrano, 2011, 2014; Pereira et al., 2013; Serrano & Ruiz-Flaño, 2007; Xavier da Silva et al., 2001; Zwolinski, 2009). However, according to Pereira et al. (2013), many key points remain unsolved. This initial set of proposals represents an important advancement, but they are difficult to implement because the connections between the methods and the concept as a whole are not yet clear and objective.

One of the greatest issues is the difficulty in creating a model capable to be implemented in different areas. Although there are models that can be applied to different areas (Carcavilla, López-Martinez, & Durán, 2007; Forte, 2014, p. 286), most of the proposals are adapted to specific study areas. The dimensions of the area, availability of data, scale, and others are some of the factors responsible for this need for adaptation. Therefore, to propose a model to assess geodiversity, it is important to consider that it cannot be complex enough to prevent replicability but neither too simple as it has to build a representation of the reality of physical element diversity.

The aim of this work was to perform a quantitative assessment of geodiversity in the municipality of Armação dos Búzios, located in the State of Rio de Janeiro, Brazil. It was performed by creating a Geodiversity Index Map, which shows the richness of geodiversity elements at a landscape scale and its distribution throughout the area. After that, an Urban Growth Map, showing the expansion of urban areas in the municipality in the last decades (from 1976 to 2006), was overlaid with the Geodiversity Index Map to assess the impacts of urban growth on the physical environment. The importance of this research is in the fact that it contributes to the consolidation of geodiversity quantitative assessment methods and provides a quantitative demonstration of the impacts of the urbanization process, which is a novelty within this subject.

1.1. Study area

The study area is the municipality of Armação dos Búzios, located in the southeastern coast of Rio de Janeiro State, Brazil (Fig. 1). It is characterized by the presence of several beaches and coves of great scenic beauty, which attracts thousands of tourists every year, consisting of the main economic activity of the municipality. The study area can be divided into two main areas: the continental area and the peninsula of Búzios; both areas are connected by a tombolo.

Geologically, it is entirely located in the Cabo Frio Tectonic Domain, which is a tectonic terrain that represents the last episode of the Gondwana amalgamation, in a 530–490-Ma tectonometamorphic event called Búzios Orogeny. It is characterized by two main lithostratigraphic units: Paleoproterozoic orthogneisses, consisting of a reworked basement, and Neoproterozoic paragneisses, associated with an ocean basin (Búzios-Palmital Basin) (Schmitt, Trouw, Van Schmus, & Pimentel, 2004). The presence of Mesozoic dykes registers the breaking of the Gondwana paleocontinent and the Atlantic Ocean opening. The northern portion of the municipality is characterized by the presence of Neogenic sedimentary rocks (Barreiras Formation) associated with fluvial processes of high energy (Morais, Mello, Costa, & Santos, 2006). There is a great variety of Quaternary deposits, most of them associated with sea-level fluctuations during the Holocene (Castro, Suguio, Seoane, Cunha, & Dias, 2014), consisting of marine and lagoonal deposits and deposits associated with gravitational and aeolian processes (Fig. 2A).

The geological diversity is reflected in the geomorphological setting. The continental area is mainly composed of low hills with gentle slopes and planed surfaces associated with eroded orthogneisses and marine and lagoonal plains, which are associated with