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Geodiversity Ecosystem Services in the Chapada Do Araripe, UNESCO World Heritage Tentative Site

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GEODIVERSITY ECOSYSTEM SERVICES IN THE CHAPADA DO ARARIPE, UNESCO WORLD HERITAGE TENTATIVE SITE

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ABSTRACT: Geodiversity provides benefits to society through the provision of ecosystem services (ES), which can occur in different landscapes, including exceptional landscapes. Similar sets of physical landscape variables, particularly from a geological, geomorphological and climatological perspective, form the Homogeneous Units of Geodiversity (HUGs). The aim of the research was to identify the HUGs and quantify the abiotic ES of each unit in the Chapada do Araripe, which is a UNESCO World Heritage tentative site. The methods employed were proposed based on a bibliographic and cartographic survey; a field questionnaire was used to assess the abiotic ES using the proposed method. The results indicate that the exceptional HUGs, under a sub-humid climate and under the direct influence of the relief, offer a greater supply of ecosystem services. The relationship between relief and climate determines the supply of services in the study area, particularly those related to regulation and support.

Keywords: Geoheritage**.** WHS. Ecosystem Services. Exceptional Landscape. Forest Disjunction

1. INTRODUCTION

The concept of geodiversity began to be discussed by geologists and geographers in the early 1990s[1]. The term geodiversity emerged in the United Kingdom in 1993, at the Malvern Conference on Geological and Landscape Conservation, and was used to describe the variety of the abiotic environment[2,3]. Gray[4] defines geodiversity as geological, geomorphological, pedological and hydrological diversity, including their assemblages, relationships, properties, interpretations and systems.

Following the same holistic definition proposed by Gray[4], Bailey et al.[5] defined geodiversity as the diversity of the Earth's surface and subsurface, encompassing geological (including soil), hydrological and geomorphological characteristics and processes. For these authors, these are the elements of geodiversity, that is, the abiotic variables.

By including climate in discussions on the concept of geodiversity, Claudino Sales [6] updated it, adding climatic diversity as part of it. Gray[7] corroborated this idea by proposing the expansion of the concept to include climate and the oceans, emphasising that atmospheric and oceanic components are broad and important parts of the global system.

Geodiversity is fundamental to the formation of landscapes, the maintenance of ecosystems and the promotion of human well-being[8]. Supported by geoconservation, geodiversity provides a range of ecosystem services that are fundamental to society, although it is less widely publicised than biodiversity[9].

Ecosystem Services (ES) correspond to the benefits provided by ecosystems [10]. According to Gordon and Barron[11], geodiversity supports different types of ES. Thus, it offers a range of benefits to people[12]. The benefits that abiotic nature provides to society are referred to by Gray, Gordon and Brown[13] as "abiotic ecosystem services". Here, the term "Geodiversity Ecosystem Services" (GES) will be used.

To understand how geodiversity provides benefits to society, several proposals for assessing GES have emerged. Gray[14] followed an approach similar to the assessment proposed by *the Millennium Ecosystem Assessment*[10], classifying ES into four categories: regulation, provisioning, cultural and supporting. This proposal was subsequently adapted by Gray, Gordon and Brown[13], who provided a systematic classification and assessment of ES. Following this same line of thought, Araújo et al.[15] presented a proposed classification of Geodiversity Ecosystem Services, adapting the methodologies developed by Gray[14], Gray, Gordon and Brown[13], Hjort et al.[9] and Gordon[12]. These methodological proposals served as the basis for the method of assessing GES proposed by Araújo, Diniz and Souza[16].

An exceptional landscape refers to an area with biotic and abiotic components that differ from those of the surrounding natural environment (biome)[16]. In other words, Ab'Saber[17] defines it as isolated features, with distinct physical and ecological characteristics, set within the general context of typical landscapes. Araújo, Diniz and Souza[16] found that the provision of ecosystem services varies according to geomorphological compartments. The authors identified a greater provision of geodiversity ecosystem services (GES) on the plateaus of the study area, demonstrating the area's exceptional nature - primarily climatic - in relation to its surroundings, with these landscapes representing an exception of a humid climate amidst a semi-arid biome. These areas offered greater benefits due to their altitude and constituent material[16]. This highlights the relationship between the elements of geodiversity - particularly lithology, relief and climate - in the provision of services.

There are areas with homogeneity in geodiversity variables (geology, pedology, geomorphology, hydrography and climate), like the classical concept of an integrated landscape, whilst these areas determine the provision of ES. These clusters correspond to the Homogeneous Units of Geodiversity (HUG), a proposal presented in this study. With the definition of HUGs, the method of Araújo, Diniz and Souza[16] can serve as a basis for the qualitative and semi-quantitative assessment of the GES, enabling comparison between different areas, in this case the proposed units.

In this context, this study aims to identify the homogeneous units of geodiversity in the Chapada do Araripe, located in the Northeast region of Brazil, and adjacent areas, and to compare the provision of GES in each HUG. The aim is to understand and identify which sectors exhibit similarity in terms of geodiversity and how this is reflected in the provision of GES. The working hypothesis is that in the HUG corresponding to the landscape of exception, there is a greater variety of GES than in the dominant surrounding landscape.

Applying the method for assessing the GES is essential to demonstrate the importance of the study area. The study contributes to the promotion of geoconservation and is aligned with two Sustainable Development Goals (SDGs): Goal 3, which aims to ensure healthy lives and promote well-being for all, and Goal 15, which aims to protect, restore and promote the sustainable use of terrestrial ecosystems[23].

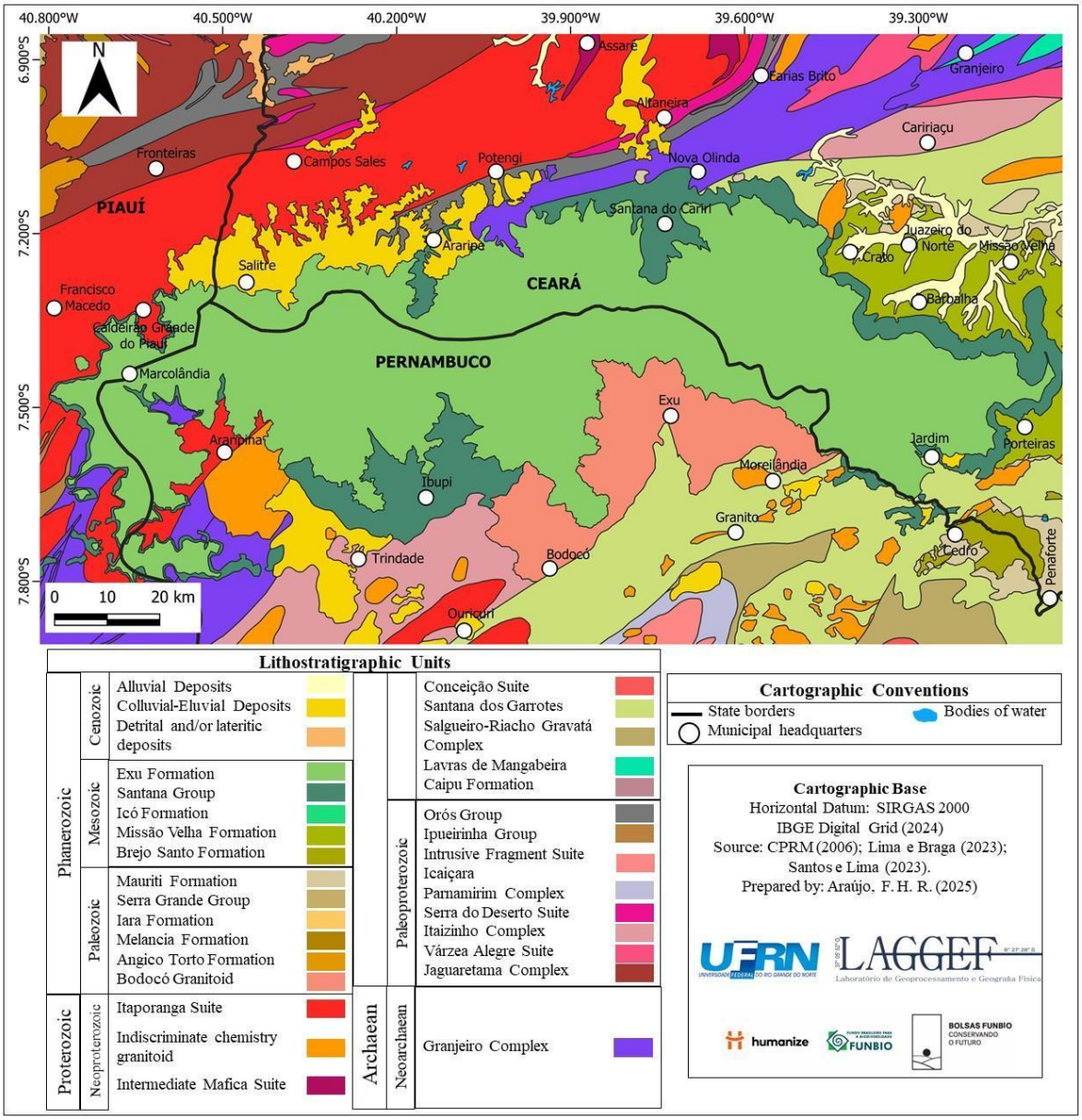
2. MATERIALS AND METHODS

2.1 Location and physical-natural characterisation of the study area

The Chapada (Plateau) do Araripe corresponds to the post-rift sequence units (Aptian/Cenomanian) of the Araripe sedimentary basin[18]. This basin is considered a geodiversity *hotspot*[19] and is home to the UNESCO Araripe Global Geopark, as well as several protected areas, such as the Araripe National Forest (Brazil's first national forest-type conservation unit), the (Revis) Soldadinho do Araripe, Private Natural Heritage Reserves (RPPNs), and is a candidate for UNESCO World Heritage Site status due to its natural and cultural values[20]. Several endemic species are found in this region, the most famous being the Soldadinho Araripe (*Antilophia bokermanni*), classified as Endangered . Another endemic species is a small crab called *Kingsleya attenboroughi*[21], which lives in some perennial springs in the Chapada do Araripe and is also classified as Endangered[22].

Chapada do Araripe and its surroundings are situated in the northern part of the Brazilian Northeast, covering the south of the state of Ceará, the north-west of the state of Pernambuco and the east of the state of Piauí. The Chapada do Araripe forms part of the sedimentary basin of the same name, an intracratonic basin formed amidst Precambrian lithologies of the Borborema Province (Figure 1).

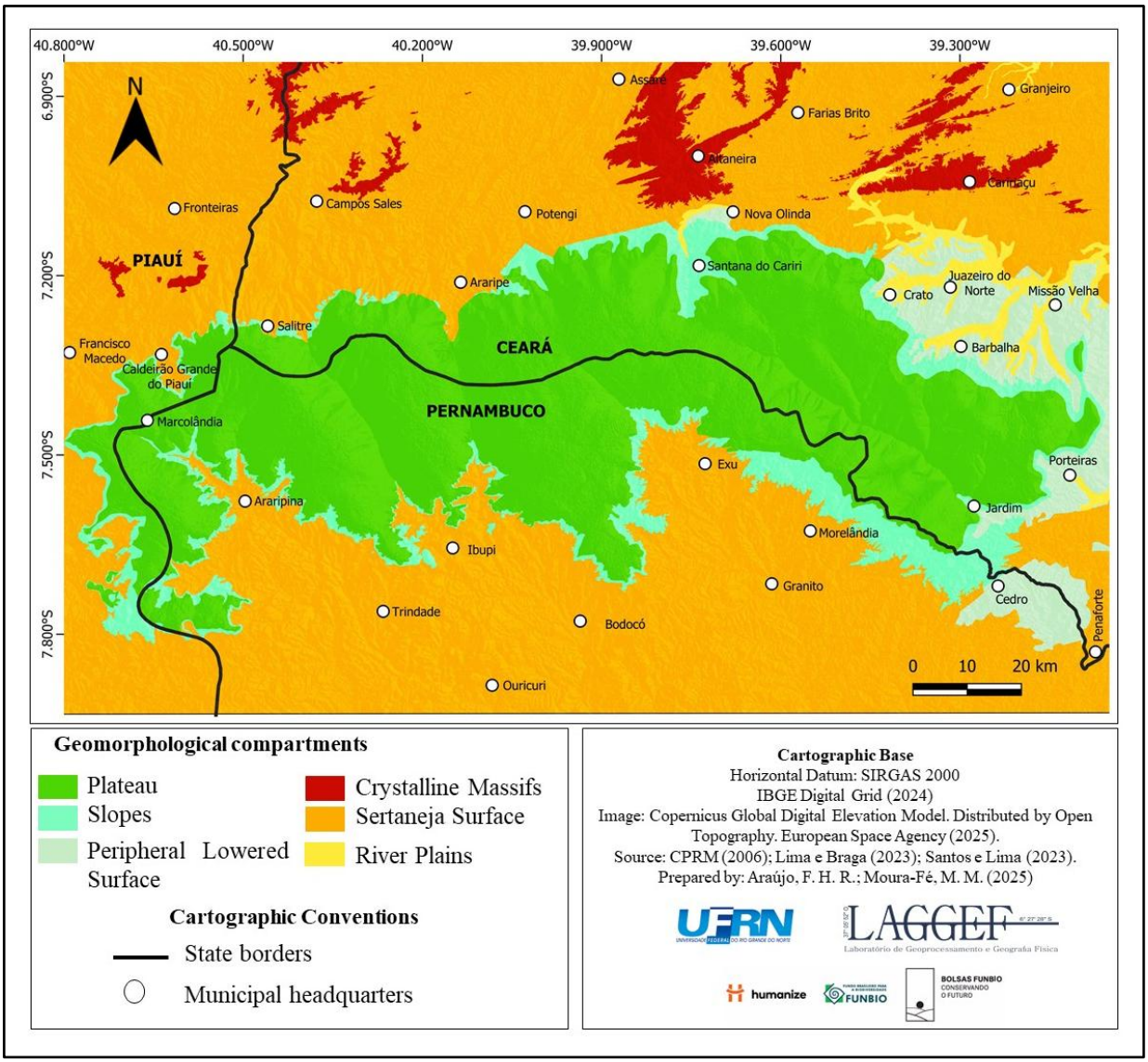
Fig. 1: Geology and Location of the Study Area.



Source: Araújo (2025)

From a geomorphological perspective, it is a sedimentary plateau comprising sedimentary rock units of the post-rift sequence that overlies the older unconformities of the Araripe Sedimentary Basin, resting on the crystalline basement [18]. In a more detailed geomorphological characterisation of the study area, six compartments were mapped: Plateau, Slopes, Lowered surface (sedimentary), Crystalline Massifs Lowered Surface (Bedrock) and River Plains (Figure 2).

Fig. 2: Geomorphological compartments of the study area.



Source: Araújo; Moura-Fé (2025).

The plateau, slopes and Lowered surface (sedimentary) are situated on sedimentary terrain. The plateau corresponds to the structural summit of the Chapada do Araripe, coinciding with the upper layers of the Cretaceous-age sedimentary rocks of the Exu Formation[24]. The slopes of Araripe rise at the edges of the plateau and consist mainly of Cretaceous rocks of the Santana Formation. In some sectors, they are bordered by the crystalline shield[25]. In this compartment, many landslide scars are identified, and there are records of talus deposits at the base[26]. The Lowered Surface (Sedimentary), on the other hand, is a flattened area that sometimes features isolated hills interspersed with outcrops with tops dissected into ridges or hills[25].

Two compartments are structured upon the crystalline basement terrain: the Lowered Surface (Berdrock) or locally known as the ‘sertaneja’ surface, and the Crystalline Massifs. The Sertaneja Surface comprises the areas structured upon Precambrian rocks of the crystalline basement, presenting extensive flattened surfaces with gently undulating topographies, generally sloping

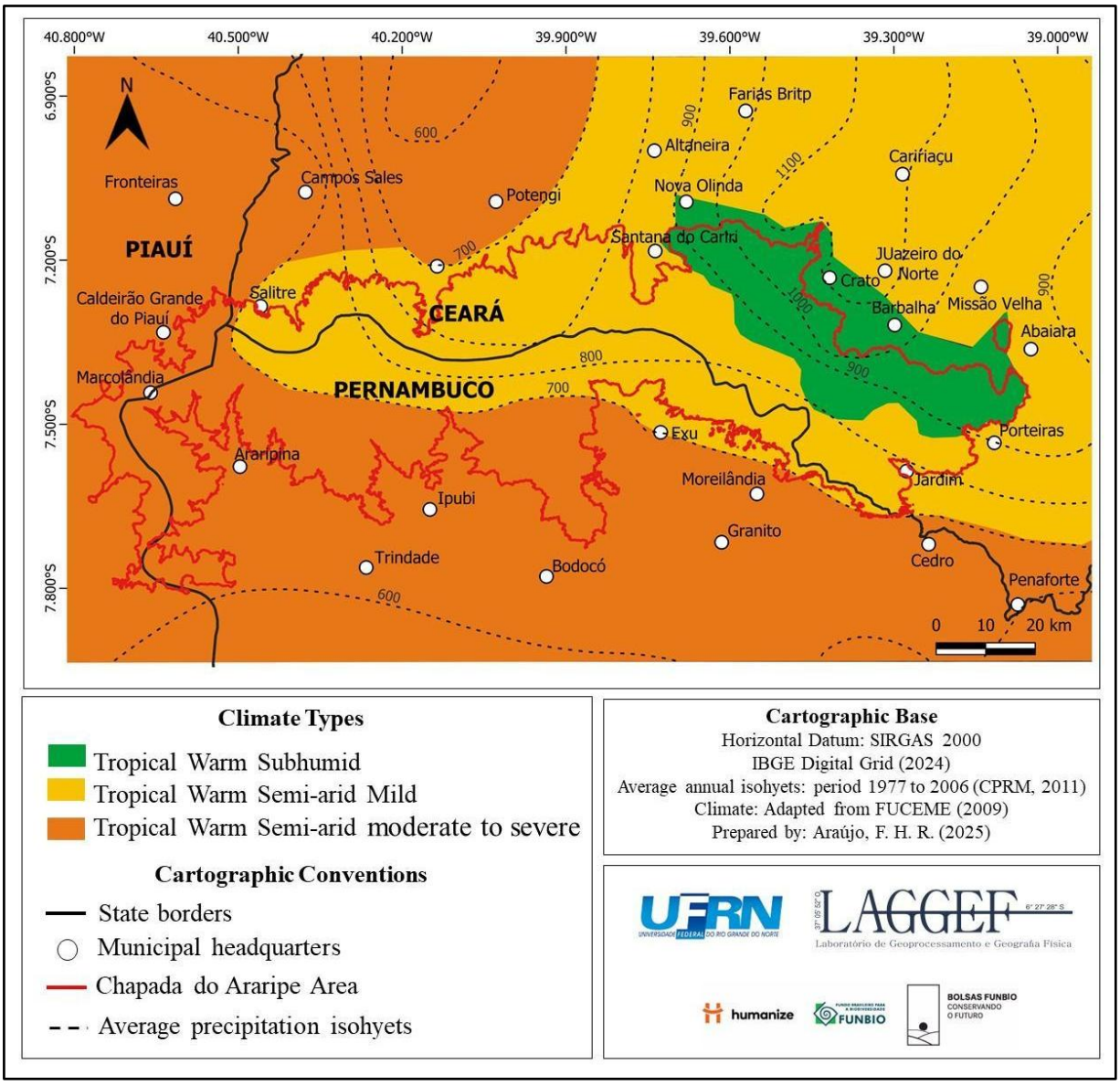
northwards. The monotony of this surface is broken by the occurrence of crystalline massifs which have been exposed at the surface through erosive processes, associated with the resistance of their constituent material. These massifs correspond to residual landforms with steep escarpments and an area exceeding 50 km²[27].

In areas of recent alluvial deposits, there are river plains, which are small areas of accumulation of sandy river sediment situated in the beds of some rivers located to the northeast of the Chapada do Araripe. According to Carvalho Neta, Corrêa and Silva[28], these are flat areas characterised by fluvial sedimentation, subject to periodic flooding and situated at altitudes ranging from 460 to 350 metres. The Salamanca River plain is the largest example of this unit.

In the Chapada do Araripe, well-developed soils such as Oxisols and Ultisols are found, alongside poorly developed soils such as Neossols[29]. Oxisols predominate in the Exu and Missão Velha formations; Ultisols develop on the sedimentary rocks of the Santana and Mauriti formations, as well as on some metamorphic rocks of the basement; and Entisols occur in the areas adjacent to the plateau [26]. According to the authors, soils of the Cambisols, Luvisols and Nitisols types are also found in this area.

The climatic pattern of the area is distinct due to the strong influence exerted by the Chapada do Araripe, resulting in variations primarily in precipitation levels and climate types (Figure 3). Most of the area is characterised by a mild Hot Tropical Semi-arid climate, with average annual rainfall between 700 mm and 900 mm. The eastern and north-eastern sectors of the plateau are characterised by a Hot Sub-humid Tropical climate with average annual rainfall between 900 and 1,100 mm. In the southern and western sectors, a moderate to strong Hot Semi-arid Tropical climate is found, with significantly lower average annual rainfall, between 500 mm and 700 mm.

Fig. 3: Climate types in the study area.



Source: Araújo (2025).

In the vicinity of the Chapada do Araripe, there are several intermittent river channels that have their sources on the slopes of the hills, such as the Salgado River and its tributaries: the Batateiras and Granjeiro rivers, the Saco and Lobo streams, the Carás river, the São José stream, the Missão Velha river, the Porcos, Cuncas, Olho D'água, Rosário and São Miguel streams[30]. The Chapada do Araripe is the major watershed between the Jaguaribe and São Francisco drainage basins[24] and its northern slope features a profusion of springs arising from the emergence of aquifers in the Exu and Santana formations, which contribute directly to the water volume of the drainage systems in this sector [31] .

The influence of the terrain on the climate increases humidity, which leads to the occurrence of patches of rainforest. According to Bétard, Peulvast and Magalhães[32], Araripe is a geographical region where species from the Caatinga, the Cerrado and the Atlantic Forest are found, these are

three of Brazil's six biomes. The Caatinga predominates in the adjacent areas and on the semi-arid slopes; the Cerrado, meanwhile, is found at the top of the semi-arid plateau; and Atlantic Forest species are more abundant in the humid part of the plateau and on the slopes, where the topography provides conditions favourable to the development of a rainforest. Moro et al.[33] classify the area as one of the high-altitude wetlands of north-eastern Brazil. According to the authors, the enclave of rainforest found in Araripe is the result of climatic fluctuations.

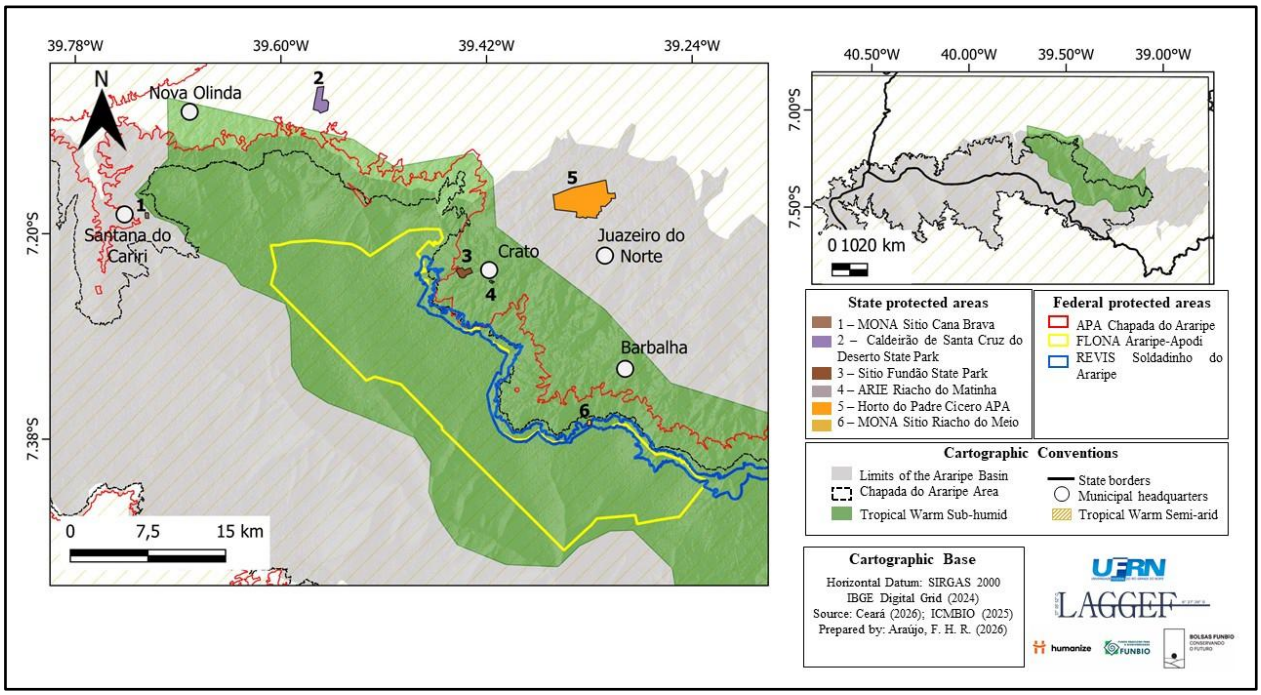
Brazil's first National Forest (Flona) was established in the Chapada do Araripe (Figure 4), a category of conservation unit that forms part of the Sustainable Use Units group[34]. The Araripe-Apodi National Forest was established by Decree-Law No. 9,226 of 2 May 1946, covering two distinct areas: one in Araripe and the other in the Chapada do Apodi. Its purpose is to protect forest resources and water sources[35]. The Soldadinho do Araripe Wildlife Refuge (Revis) was also recently established at federal level by Decree No. 12,492 of 5 June 2025 [36]. Also within the area lies the Chapada do Araripe Environmental Protection Area (APA), established by Federal Decree of 4 August 1997[37] .

Fig. 4: Overview of part of the Araripe National Forest.



In addition, there are other protected areas integrated into the state conservation system of Ceará State[38] . These are: Horto do Padre Cícero APA (Juazeiro do Norte); Area of Relevant Ecological Interest – ARIE Riacho do Matinha, Caldeirão de Santa Cruz do Deserto State Park and Sítio Fundão State Park (Crato); Natural Monument – MONA Sítio Cana Brava (Santana do Cariri); and Natural Monument – MONA Sítio Riacho do Meio (Barbalha). As can be seen in Figure 5, most protected areas are situated in the sub-humid tropical climate zone.

Fig. 5: Protected areas in the Chapada do Araripe.



Source: Araújo (2025).

The abundance of fossil records of Lower Cretaceous fauna has made Araripe internationally renowned for its rich palaeontological heritage, which was a key factor in the creation of the first UNESCO Global Geopark in the Americas and the Southern Hemisphere. Established in 2006, the Araripe Geopark features geosites open to visitors and offers ample scope for expansion, as there are other sites of geological interest that have been identified but have not yet been fully inventoried[39]. There are currently 11 geosites open to the public. These are: Colina do Horto (Juazeiro do Norte), Arajara, Batateiras, Mirante do Caldas and Riacho do Meio (Barbalha), Floresta Petrificada and Cachoeira de Missão Velha (Missão Velha), Pedra Cariri and Ponte de Pedra (Nova Olinda), Parque dos Pterossauros and Pontal da Santa Cruz (Santana do Cariri).

In addition to the area's geological richness, the diverse cultural tradition passed down from generation to generation is a notable feature. Currently, Chapada do Araripe is on the tentative list of UNESCO World Heritage Sites due to its natural and cultural values[20, 40].

2.2 Methodological procedures

Initially, bibliographic research and cartographic surveys of the study area were carried out. Subsequently, fieldwork was carried out with the aim of verifying the data produced in the GIS

environment, as well as completing the data sheets based on the methodology adapted from Araújo, Diniz and Souza[16]. Finally, the data obtained in the field at each identified HUG were discussed, along with an assessment of the degree of relevance of the SE.

The literature review was conducted on digital platforms such as *Web of Science* and *Scopus* with searches on the topics "Geomorphology" and "Araripe" to characterise the study area, and on the themes of "geodiversity" and "geodiversity ecosystem services".

Among the cartographic materials, maps of geology, geomorphology and HUG were produced using QGIS 3.36. For the geological data, vector data were used from the map of potential for ornamental rocks in the state of Ceará, produced by Lima and Braga[41]; from the geological mapping of the state of Pernambuco, by Santos and Lima[42]; and from the geological map of Piauí, produced by CPRM[43]. To delineate the geomorphological compartments, mapping was carried out down to the 3rd taxon. For this purpose, the geological information and the Digital Elevation Model (DEM), extracted from *the Copernicus Global Digital Elevation Model* and distributed by the European Space Agency's *Open Topography*[44], were considered.

The geological and geomorphological data were cross-referenced with climate data to delineate the homogeneous units of geodiversity (HUGs), with HUGs being geological-geomorphological units distinguished by the semi-arid and semi-humid tropical climates present in the area. This is because the interaction between climate and relief alters the supply of ES.

For an area to be classified as a HUG, it must meet at least three of the following criteria:

● Geomorphological – 75 per cent of the terrain must fall within the same class (Flat, Gently undulating, Undulating, Strongly undulating, Mountainous and Rugged);

● Geological – 75 per cent of the rocks must belong to the same major group (crystalline or sedimentary);

● Climatic – Variation of less than 300 mm in average annual rainfall within the same HUG;●

● Pedological – 75 per cent of soils within the same depth class (shallow or poorly developed, generally less than 1 metre deep; and deep or well-developed, more than 1 metre deep).

The classification of geodiversity ecosystem services was carried out using a semi-quantitative approach with a binary assessment to indicate the presence or absence of benefits. This analysis was based on field data collection, internet research, a review of the academic literature and official documents, using a form adapted by Araújo, Diniz and Souza[16], which groups the benefits into four categories: regulatory, supply-related, cultural and support-related (Table 1).

Table 1. Classification of Geodiversity Ecosystem Services

1. **Regulation Services:** Includes processes aimed at the natural control of environmental conditions, such as air, water and soil. It controls the availability of these resources, their quantity and quality.	
CATEGORIES/BENEFITS	**PARAMETERS**
1.1 Climate and Air Quality Regulation – Geodiversity influences the climate both locally and globally, for example through the effects of topography on temperature and precipitation. Aspects of the abiotic environment also play a key role in regulating the climate, through rock weathering, carbon sequestration and the release of greenhouse gases, as well as by removing chemicals from the atmosphere, which influences many aspects of air quality.	**Present:** The characteristics of the physical environment directly affect the climate and air quality; for example: ● Topography may contribute to an increase in humidity of at least 25 per cent compared with the surrounding area; ● Topography may provide ideal ventilation conditions which, combined with altitude, reduce the temperature by at least 4 °C compared with the surrounding area. **Absent**: There is no influence of any kind.
1.2 Atmospheric and/or Oceanic Regulation - Atmospheric and oceanic circulations play a vital role in regulating the world's climate and habitability.	**Present**: The abiotic environment and associated geomorphological features play a decisive role in atmospheric and oceanic regulation; for example: ● When the relief acts as an orographic barrier to air masses; ● When the relief facilitates the movement of air masses to areas further inland from the coast. **Absent**: There is no influence of any kind.
1.3 Water Regulation - The timing and magnitude of runoff, flooding, water storage and aquifer recharge can be strongly influenced by topography, soil, surface deposits and bedrock.	**Present**: When the characteristics of the abiotic environment help to mitigate natural risks, they improve water quality and provide drinking water, which is used to maintain habitats and for human consumption both in situ and ex situ. For example: ● Rocks with high porosity increase infiltration, which helps to recharge the water table and aquifers; ● Flat topography, associated with sedimentary formations, helps to increase infiltration; ● Soils at least 2 metres deep, which have the capacity to store water; ● The presence of perennial springs, which may occur where sedimentary rock meets the crystalline bedrock. **Absent**: There is no influence of any kind.

1.4 Water Quality/Water Purification and Waste Treatment - Rock, surface deposits and soil act as natural filters, providing the 'fabric' for regulating water quality. The unsaturated zone (the soil and subsurface geology that purifies percolating water) filters out particles, organic waste and other pollutants before the water percolates down to the aquifer. This service recognises the capacity of geodiversity components and processes to contain, dilute, mitigate and decompose pollutants.	**Present**: 'Cleaner' water for groundwater aquifers and surface water bodies and their dependent habitats. This may bring economic benefits by reducing subsequent requirements for the treatment of the water supply. For example: ● Porous rock formations have a high infiltration capacity, contributing to water purification and improved water quality; ● Deep, sandy soils have high permeability and offer favourable conditions for improving water quality. **Absent:** Where there is no water purification or where unpolluted water bodies are used solely for aesthetic purposes.
1.5 Flood control - Although flood control is often listed as an ecosystem service, many of the processes involved are physical and ecological. For example, soil and subsoil sediments absorb large quantities of rainwater, reducing surface runoff and, consequently, delaying and moderating the delivery of water to river channels, which reduces flooding.	**Present**: The characteristics of the abiotic environment play a key role in reducing the impacts of flooding, for example: ● An area with porous sedimentary material promotes infiltration; ● An area with highly fractured rock, which reduces surface runoff; ● An area with sandy soils of high porosity; ● When the climate favours the growth of dense vegetation, contributing to an increase in the amount of leaf litter – a biotic component of the soil – which mitigates the impacts of flooding by promoting water absorption by the other soil layers. **Absent**: There is no influence of any kind.

1.6 Natural Hazards and Erosion Control – Protection of people, property and land against natural hazards, such as floods, erosion and landslides.	**Present:** When the abiotic environment contributes to: ● The regulation of river floods through natural flood defences and natural floodplains; ● Protection against erosion of rivers and floodplains, and the protection of sediment deposition through the maintenance of natural channel flows and sediment regimes; ● Regulation of coastal flooding through natural migration from the sea inland and protection provided by natural flood defences (salt marshes, sand dunes); ● Protection against coastal erosion through the maintenance of dunes and beach ridges and the natural circulation of sediments; and ● Protection of slopes and against soil erosion, and risk assessment through the analysis of rock and soil properties, slope stability and historical patterns of process activity. **Absent**: No influence of any kind

2. Provision Services: Responsible for making material goods available to human societies. This is the easiest to understand, as in most cases there is a monetary value associated with the good, which is then treated as a product.

CATEGORIES/BENEFITS	PARAMETERS
2.1 Freshwater supply – Geology provides the framework for aquifers and supports surface water systems. Soils, subsurface geology and topography influence the storage potential of surface water, whilst the properties of aquifers influence the storage and production potential of groundwater.	**Present**: Where the abiotic environment provides: ● Natural sources of fresh water, whether surface or groundwater, and mineral water; ● The abstraction of surface water or groundwater for public water supply, industrial use or private domestic use; ● Sources to sustain water-dependent habitats and maintain base flow in rivers. **Absent**: There is no evidence.
2.2 Industrial materials – Resources from the abiotic environment provide the raw materials and essential inputs required for industry to function.	**Present:** Resources used in industry are extracted in the area. For example: ● Metallic minerals are mined there; ● Exploration is at an early stage in the area, with reserves of raw materials that may be used by industry in the future.

	Absent: There are no industrial resources in the area.
2.3 Energy (renewable and non-renewable) - Geology, topography and natural processes help to provide both renewable forms of energy (hydroelectric, geothermal, tidal, wave, solar and wind) and non-renewable forms (coal, oil, natural gas, etc.).	**Present**: The abiotic environment provides the basis for the supply of energy resources, reflecting the extent of energy extraction. For example: ● The geology of the area provides energy resources that are extracted and used for the generation of non-renewable energy; ● The existence of hydroelectric power stations that have been built in areas of rugged terrain and crystalline rock formations; ● The existence of wind farms in areas where the combination of topography and climate provides favourable wind conditions; ● The existence of solar power stations in areas characterised by a climate with high levels of sunshine and low cloud cover, combined with a flat topography. **Absent**: It does not provide the means for energy exploitation.
2.4 Nutrients and minerals for healthy growth - When the soil provides minerals and nutrients essential for the production of food, fibres, fuels, biochemicals, pharmaceuticals and natural remedies.	**Present:** Soil type, together with mineralogical characteristics, are key factors determining the growth or production associated with a particular activity. ● Agriculture, herbalism and/or phytotherapy in areas with naturally fertile soils; ● Soils with low fertility, where the topography allows for agricultural activities. **Absent**: There are no such relationships.
2.5 Ornamental resources – Supply of rocks, fossils, minerals and aggregates for decoration and landscaping.	**Present:** Where there is evidence of the quarrying of rocks and minerals for decorative purposes. For example: ● The area is home to the extraction of precious stones, precious and semi-precious metals, granite and marble worktops, as well as slate flooring in kitchens, rocks and river stones in gardens, Caithness slabs for paving, slate, fossils, polished stones and minerals for domestic ornaments;

	● Where extraction is not carried out for economic purposes, but solely for decorative purposes, using traditional methods and involving minerals or rocks. **Absent**: There are no such relationships.
2.6 Construction materials – Extraction of rocks, sediments and other materials for civil construction.	**Present**: When the abiotic environment provides the means to extract essential raw materials for the construction industry. For example: ● When it involves the extraction of sediments, rocks, sand and other minerals used in the construction industry; ● When it involves the extraction of materials used in the construction industry for its operations. Example: the extraction of limestone for the production of lime. **Absent**: There are no links.
3. Cultural and Knowledge Services: This corresponds to society's relationship with some abiotic aspect of the environment, due to its social or community importance. Knowledge services, in turn, relate to proposals for using the abiotic environment as a classroom and laboratory, for purely scientific and educational purposes.	
CATEGORIES/BENEFITS	**PARAMETERS**
3.1 Cultural diversity – The diversity of the physical environment is a factor that influences cultural diversity and cultural identity.	**Present:** When the cultural diversity of a place is directly linked to its geodiversity and/or the physical environment influences local cultural characteristics. For example: ● Churches and towns carved out of rock; ● Traditional events linked to some aspect of geodiversity; ● When the local cuisine reflects some abiotic aspect. **Absent**: There are no such relationships.

3.2 Spiritual and religious values and cultural meanings - Natural rock formations and landfills often have associated religious or spiritual values, which are also present in local folklore and legends.	**Present**: There is a strong link between the physical environment and spiritual and religious values, as well as cultural meanings. For example: ● The existence of shrines on high ground, which are cherished by local residents and people from other areas; ● The presence of wayside crosses or religious monuments on the summits of elevated areas; ● Rocky outcrops or elevated areas that hold religious and/or cultural significance as places of worship or which are associated with folk legends. **Absent**: There are no such relationships.
3.3 Knowledge systems – Society benefits from knowledge of the Earth's physical properties, materials, processes and history in many ways (for example, through applied geology, geological engineering, environmental geology, medical geology and geoforensics). Records of past climatic and environmental changes, preserved in a variety of archives (such as ice cores, ocean sediments, landfills and lake sediments), provide a long-term perspective on Earth system processes, ecosystem dynamics, trends and human interactions. These records provide baselines for environmental monitoring and forecasting, and can indicate possible ecosystem responses to future changes in climate and other factors.	**Present**: Environmental characteristics provide a good example and offer fundamental insights for knowledge systems. For example: ● When an area of interest contains elements that serve as a baseline for understanding various evolutionary processes in Earth's history, climate change, amongst others. ● The existence of scientific research (theses, dissertations and articles) based on the study of elements of the abiotic environment present in the area. **Absent**: There are no such relationships.
3.4 Education – Geodiversity provides the basis for formal and non-formal education for people of all ages through outdoor learning and educational opportunities.	**Direct**: Environmental characteristics provide a good example and can be used for education at different levels: primary, secondary and higher education. For example: ● Frequent field trips aimed at studying the abiotic characteristics of the area and/or its evolutionary process. **Absent**: There are no such relationships.
3.5 Artistic inspiration - Geodiversity provides a rich source of inspiration for art, literature, poetry, music, sculpture, national symbols, architecture, built heritage and gardens.	**Present**: When geodiversity is used as a source of inspiration in artistic representations: For example: ● The existence of bibliographies, evidence and accounts showing that geodiversity was a source of inspiration; ● When one or more elements of geodiversity are represented in official symbols (flag, coat of arms, anthem, etc.);

	● When one or more elements of an area's geodiversity are depicted on the branding of various products (food, drink, footwear, etc.). **Absent**: There are no reports or evidence of artistic inspiration.
3.6 Aesthetics – Many people find natural beauty and aesthetic value in various aspects of the natural environment, such as interesting, beautiful and dramatic landscapes and views, as well as in silence, tranquillity and peace.	**Present**: A landscape that is aesthetically rich and pleasing, characterised by the presence of at least two of the following features: ● Colour contrast (with at least three contrasting colours); ● Vertical relief (>50 metres); ● Presence of bodies of water. ● A landscape featuring ruins and/or isolated residual hills **Absent:** It does not include two of the points.
3.7 Social relations – Changes in ecosystem services (such as the availability of fresh water and the regulation of floods or erosion) can affect social relations, particularly in cultures that maintain strong links with their local environments. Volunteering through Local Geoconservation Groups can also provide opportunities for social interaction.	**Present**: Ecosystem services play a fundamental role in the functioning of the local community. For example: ● One or more elements of geodiversity directly influence the social relations within a community (a watercourse shapes a fishing community, a mineral shapes a mining community, a particular type of climate, rock and/or soil shapes a specific economic activity, etc.). ● When an area is used for social interactions based on one or more abiotic elements (such as informal gatherings, picnics and recreational activities). **Absent**: There are no such relationships.
3.8 Sense of place - Many people value the sense of place associated with recognised features of their environment, such as natural rock formations and landscapes, and the perception of 'safety' created by these features.	**Present**: The physical characteristics of the area are appreciated by residents, who associate them with a sense of place. For example: ● When a rock formation or land feature is depicted as a symbol that represents the place for its inhabitants; ● When a place has a name referring to an element of geodiversity. **Absent**: There are no such relationships.

3.9 Cultural Heritage and Geoheritage - Geosites associated with major developments in geoscience form part of the cultural value of geoheritage. Other geosites are significant for their historical, literary or artistic associations, or for other cultural meanings. Geodiversity underpins the landscape character of the sea and of different types of cultural landscape. The use of local or traditional stones and other geological materials in the built environment, as well as the conservation of cultural landscapes, contribute to an area's cultural heritage and its landscape character. Cultural memories are often expressed through natural features such as mountains, waterfalls and rock formations.	**Present**: Geodiversity is closely linked to the cultural identity that underpins the existence of heritage. For example: ● When an area contains inventoried sites that are significant in terms of various geoheritage parameters (geological, geomorphological, pedological, speleological, hydrological, amongst others); ● When the area is listed as cultural heritage and has a strong link to geodiversity. **Absent**: There are no sites of relevance in the area.
3.10 Health and well-being – Geodiversity contributes to people's health and well-being through the contemplation of and sounds of nature.	**Present**: The area has distinctive physical and natural features that play a key role in people's wellbeing and health. Some examples are: ● The sound of water in watercourses such as streams and waterfalls; ● The use of hot springs for their therapeutic properties; ● Contemplating minerals, rocks or landforms. **Absent:** There are no such relationships.
3.11 Nature-based Recreation and Tourism - People often choose where to spend their leisure time based on the natural or cultural characteristics of a particular area. Physical characteristics (geodiversity) underpin the landscape character, valued habitats and ecosystems, as well as the aesthetic and other cultural qualities of a region. They provide opportunities for outdoor recreation, such as hiking, rock climbing, caving, skiing and adventure activities, as well as leisure. They also offer a peaceful retreat for relaxation and reflection, contributing to people's health and well-being. They also support geotourism, which in turn provides a source of employment (for example, in geoparks) and a range of relational and other benefits, described above, which contribute to people's health and well-being, as well as to their lifelong educational and personal development.	**Present**: When geodiversity provides the conditions for recreation, thereby facilitating tourism. For example: ● The area contains sites regarded as key destinations for the local population's recreational activities, which usually attract a number of tourists. **Not applicable**: The area is not used for recreational activities.

4. Support Services: These are services in which geodiversity provides resources for human activities or for nature itself, and which depend directly on soils and rocks to be carried out. They include the provision of resources for certain human activities and for the planet's biota.

CATEGORIES/BENEFITS	PARAMETERS
4.1 Soil formation processes – Aspects of the abiotic environment facilitate soil formation through the weathering of rocks and other source materials (including those derived from erosion and sediment deposition), serving as a basis for plant growth and the maintenance of habitats.	**Present:** Geodiversity promotes pedogenesis, enabling the formation of soils. For example: ● An area with strong pedogenic activity, favouring the presence of well-developed soils; ● Well-developed soils that provide the basis for the occurrence of dense forests. **Absent:** No soil formation.
4.2 Burial and storage - The Earth's physical resources have long been used for the burial of bodies, whether in the ground (as in graves) or in monuments built above ground, such as pyramids or, on a smaller scale, cairns or dolmens. A diverse range of rock types is also used by modern stonemasons to make gravestones, although an important property here is durability, particularly in terms of retaining excrement.	**Present:** Geodiversity determines the suitability of sites for waste disposal and storage. For example: ● The presence of sites for the storage of nuclear waste, landfill sites, graves, or as raw material for the construction of mausoleums. **Absent:** There are no such relationships.
4.3 Platform for human activity – Geodiversity provides a platform for construction and infrastructure (e.g. flat land on elevated beaches or river terraces).	**Present:** The benefits arise from the platform provided by geodiversity, for example: ● The existence of urban settlements on flat land; ● The construction of weirs in gorges or ravines; ● The presence of telecommunications masts, cable cars, funiculars and so on in elevated areas; ● The development of infrastructure based on some element of geodiversity that provides the foundation for a particular economic activity. **Absent:** It is not used as a platform for human activities.
4.4 Biogeochemical cycling – The natural and continuous circulation of vital elements (e.g. carbon and nitrogen), comprising exchanges between the atmosphere, the geosphere and living organisms.	**Present:** Provision of minerals and nutrients necessary for the functioning of the biogeochemical cycle. For example: ● Areas with deep soils favour the development of forests, which aid biogeochemical cycling; ● Areas characterised by high rates of chemical weathering, high temperatures and water flow ensure the dissolution and transport of chemical elements; ● Areas with a semi-arid tropical climate, where rainfall is concentrated in a specific period of the year and there

	is an alternation between dry and wet seasons, contribute to the presence of deciduous species that are highly efficient at carbon sequestration. **Absent:** There are no such relationships.
4.5 Habitat Provision – The physical environment generally plays a HUGe role in providing habitats for biodiversity, but this fact seems to be rarely recognised by ecologists.	**Present:** The physical environment determines the characteristics of the habitat and, consequently, the presence of certain species. For example: ● The presence of endemic species in areas where natural conditions are influenced by some aspect of geodiversity; ● The presence of rare or endangered species; ● Caves that are used as habitats by certain species such as bats, arachnids, etc.; **Absent:** There are no such relationships.

Source: Adapted from Araújo, Diniz and Souza (2024).

Following data collection, the results were analysed and discussed, with an assessment of the degree of relevance of the ES, adapting Burkhard's method[45], which evaluates the spatial distribution of services using a matrix that divides the degree of relevance into six classes with values ranging from 0 to 5. Araújo, Diniz and Souza [16] also adapted this method to classify the degree of relevance of the GES, considering the number of benefits offered in each category.

This proposal takes into account the six categories proposed by Burkhard[45]. The percentage is allocated according to the number of benefits present in each category. The limits are not perfectly symmetrical because they reflect the actual behaviour of the phenomenon. To this end, it was considered that the 'Not Relevant' and 'Very High' categories serve to isolate the most exceptional cases, and have therefore been set with narrower ranges (of around 10 percentage points). The other intermediate ranges, however, are proportional to one another, taking into account equal intervals of 20 percentage points. The details are set out in Table 2:

Table 2. Degree of relevance of geodiversity ecosystem services by category.

Categories	Total benefits	Maximum score (%)	Score awarded (%)	Degree of relevance based on score awarded	Relevance score

Regulation	6	100%	0–10	0	Not relevant
			11 – 30	1	Very low
			31 – 50	2	Low
			51 – 70	3	Medium
			71 – 90	4	High
			91–100	5	Very high
Provision	6	100%	0–10	0	Not relevant
			11 – 30	1	Very low
			31 – 50	2	Low
			51 – 70	3	Medium
			71 – 90	4	High
			91–100	5	Very high
Cultural and Knowledge	11	100%	0–10	0	Not relevant
			11 – 30	1	Very low
			31 – 50	2	Low
			51 – 70	3	Medium
			71 – 90	4	High
			91–100	5	Very high
			0–10	0	Not relevant

Support	5	100%	11 – 30	1	Very low
			31 – 50	2	Low
			51 – 70	3	Medium
			71 – 90	4	High
			91–100	5	Very high

Source: Adapted from Burkhard [45]; Araújo, Souza and Diniz [16].

To determine the relevance of an area, the number of benefits offered in each category is taken into account; from this, the percentage of services identified is calculated in relation to the total number of possible benefits within that service. For example, a particular area has 5 regulatory benefits out of a possible 6, so 5/6 x 100 = 83.3 per cent; in other words, 5 is equivalent to approximately 83 per cent of 6 benefits, placing it in the 'high relevance' category.

The overall relevance score is calculated by adding up all the percentages for the categories and dividing the total by 4, as shown in Table 3.

Table 3. Degree of overall relevance of geodiversity ecosystem services.

	Total benefits	**Maximum score (%)**	**Score awarded (%)**	**Relevance score based on the score awarded**	**Relevance score**
Geodiversity ES	28	100%	0 – 10	0	Not relevant
			11 – 30	1	Very low
			31 – 50	2	Low
			51 – 70	3	Medium
			71 – 90	4	High
			91–100	5	Very high

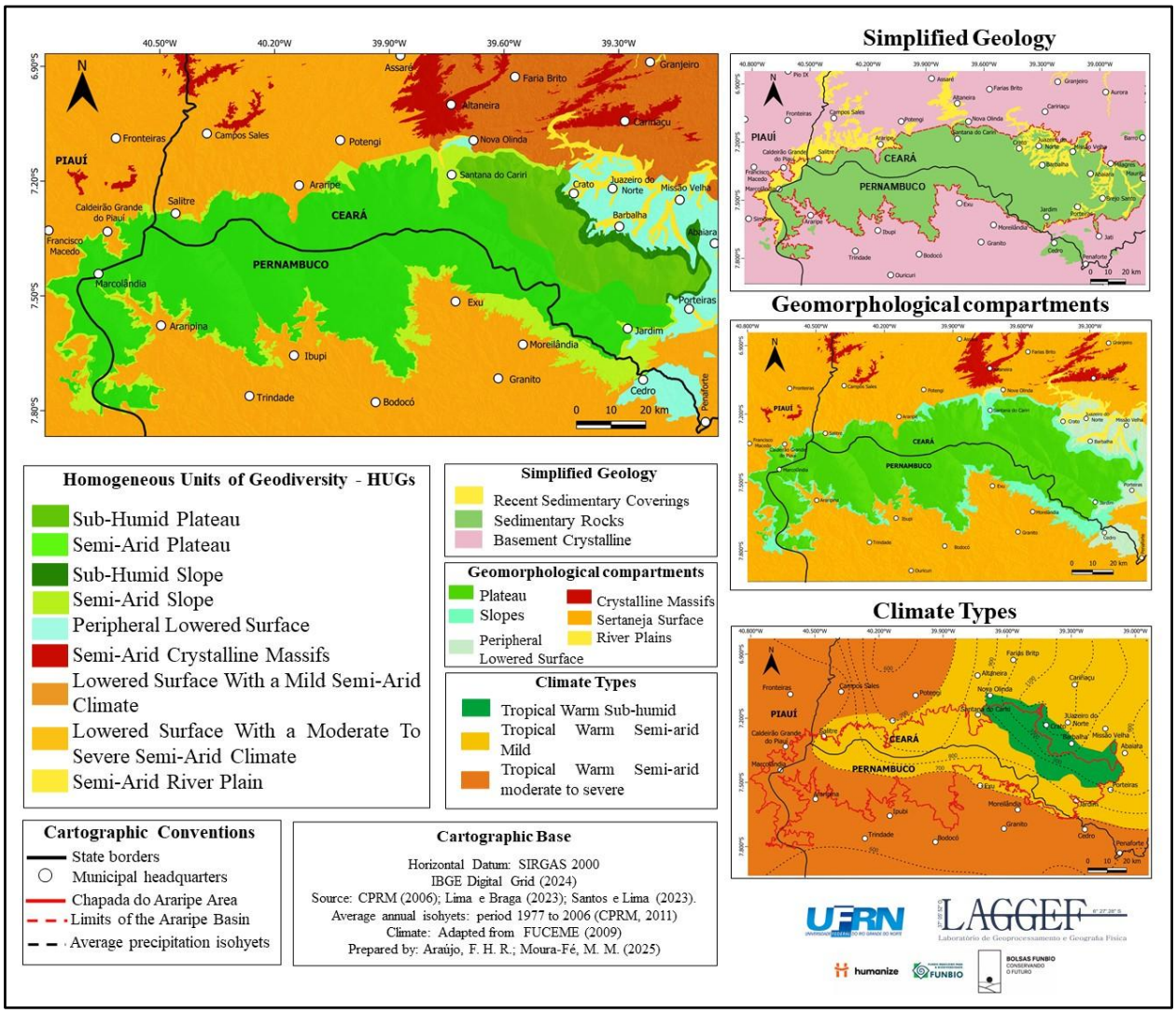
Source: Adapted from Burkhard [45] ; Araújo, Souza and Diniz [16] .

3. RESULTS

3.1 Homogeneous Geodiversity Units – HUG

Upon analysing the abiotic elements that make up the geodiversity of the Chapada do Araripe and adjacent areas, 9 HUGs were delineated: Sub-Humid Plateau; Semi-Arid Plateau; Sub-Humid Slope; Semi-Arid Slope; Peripheral Lowered Surface; Semi-Arid Crystalline Massifs; Lowered Surface With a Mild Semi-Arid Climate; Lowered Surface With a Moderate To Severe Semi-Arid Climate; Semi-Arid River Plain. Figure 6 shows the spatial distribution of these units within the study area.

Fig. 6: Homogeneous Units of Geodiversity (HUG) in the Chapada do Araripe and adjacent areas.



Source: Araújo; Moura-Fé (2025).

The HUGs in the study area exhibit similarities in the physical variables of the landscape, particularly from a geological, geomorphological and climatological perspective. Table 4 provides a summary of each unit present in the study area.

Table 4. Characteristics of the HUGs in Chapada do Araripe and adjacent areas.

HUG	LITOLOGY	GEOMORPHOLOGY	SOILS	CLIMATE	Vegetation shaped by geodiversity	AN EXCEPTIONAL LANDSCAPE?
Sub-Humid Plateau	Sedimentary – Exu Formation	Sedimentary Plateau	Clay soils and Oxisols.	Sub-humid Tropical.	Evergreen forest and Cerrado (savannah) shaped by the interaction between soil, relief and atmosphere.	YES
Semi-Arid Plateau	Sedimentary – Exu Formation	Sedimentary Plateau	Clay soils and Oxisols.	Mild Semi-arid Tropical.	Common Caatingas of the semi-arid region.	NO
Sub-Humid Slope	Sedimentary – Santana Formation	Slope	Lithic Entisols, Ultisols, Oxisols.	Sub-humid Tropical.	Evergreen forest influenced by the interaction of climate, relief and soi.l	YES
Semi-Arid Slope	Sedimentary – Santana Formation	Slope	Litholic Entisols, Ultisols, Oxisols	Mild Semi-arid Tropical.	Common Caatingas of the semi-arid region.	NO
Peripheral Lowered Surface	Sedimentary – Barbalha, Abaiara, Missão Velha, Brejo Santos and Mauriti formations	Peripheral Lowered Surface	Latossols, Vertissols.	Sub-humid Tropical and Mild Semi-arid Tropical.	Common Caatingas of the semi-arid region.	NO
Lowered Surface with Mild Semi-Arid Climate	Crystalline – granites and gneisses	Sertaneja surface	Luvisols and Entisols.	Mild Semi-arid Tropical.	Common Caatingas of the semi-arid region.	NO

Lowered Surface With Moderate To Severe Semi-Arid Climate	Crystalline – granites and gneisses	Sertaneja surface	Luvisols and Entisols.	Mild semi-arid tropical.	Common Caatingas of the semi-arid region.	NO
Semi-Arid Crystalline Massifs	Crystalline – granites and gneisses	Crystalline Massifs and Inselbergs	Entisols – Lithols and Regolits.	Tropical Semi-arid.	Common Caatingas of the semi-arid region.	NO
Semi-Arid River Plain	Alluvial deposits	Plain	Fluvial Entisols.	Semi-arid Tropical.	Common Caatingas of the semi-arid region and riparian forest.	NO

Sub-Humid Plateau: This area encompasses part of the Araripe Plateau, which lies on sandstone bedrock and exhibits characteristics of a sub-humid tropical climate. The plateau reaches altitudes of up to 900 metres, and in some areas slightly higher. It is characterised by flat features due to the weathering of sandstone from the Exu Formation[25] ,which consists of highly porous rocks[31]. This high porosity of the rocks contributes to the maintenance of the tabular topography, even in the face of high rainfall rates. Well-developed soils are found, notably those of the Latosols class, which develop within the Exu Formation. These are soils at an advanced stage of weathering, deep and well-drained[46]. Average rainfall ranges from 800 mm to 1000 mm, with temperatures ranging from 20°C to 27°C; the soil-relief-atmosphere interaction shapes an exceptional landscape featuring an evergreen tropical forest amidst the Brazilian semi-arid biome dominated by caatingas.

Semi-Arid Plateau: covers most of the Araripe sedimentary plateau, with lithology and soils similar to the HUG of the sub-humid plateau, differing only in the climatic characteristics of the semi-arid region, with annual rainfall ranging from 700 mm to 800 mm. The decrease in rainfall is due to the relationship between relief and climate, as the region's two main rainfall systems, the Intertropical Convergence Zone (ITCZ) and the Upper-Level Cyclonic Vortex (ULCV), are most intense in the eastern and north-eastern parts of the Chapada do Araripe, losing strength as they move towards the western portions of the plateau.

Sub-Humid slopes: these correspond to the edges of the eastern and north-eastern sectors of the Chapada do Araripe, which are built upon Cretaceous sedimentary rocks of the Santana

Formation. In this area, soils of the Ultisols, Oxisols and Lithic Entisols classes are found, with the presence of lateritic crust in some sectors. It is the rainiest sector of the plateau, with rainfall varying between 1000 mm and 1100 mm. The orographic barrier formed by the plateau contributes to increased rainfall in the surrounding area[30]. This area is also characterised by the presence of several perennial springs. It is an exceptional landscape with evergreen tropical forest vegetation that extends continuously into the sub-humid plateau

Semi-Arid Slopes: these are escarpments composed of Cretaceous sedimentary rocks of the Santana Formation and crystalline rocks in some sectors, with low rainfall that characterises them as having a semi-arid climate. They share lithological and pedological similarities with the sub-humid slope, with climate being the variable of geodiversity that distinguishes them. The morphology of the slopes varies depending on the sector, appearing in some places as a cuesta-like escarpment and in others as a glint [24]. Average annual rainfall is 500 mm to 700 mm.

Peripheral Lowered Surface: this unit corresponds to the dissected part of the Chapada do Araripe, characterised by the presence of sedimentary rocks and a sub-humid climate. It consists of sedimentary rocks from the early stages of the sedimentary basin's formation: the pre-rift phase (Brejo Santo and Missão Velha Formations), the rift phase (Abaiara Formation) and the post-rift phase (Barbalha Formation). There is evidence of Latosols developed on the rocks of the Missão Velha Formation and Vertosols in the flat or gently undulating areas of this unit[26]. Annual rainfall reaches 1100 mm, characterising a sub-humid climate.

Lowered Surfaces With Semi-Arid Climate: These are areas characterised by topographies ranging from flat to gently sloping and dissected, with a low gradient. Generally, they reach altitudes between 350 and 450 meters and can reach 500 metres near the northern sector of the Chapada do Araripe. Located on terrain of crystalline basement lithologies, the presence of Brazilian granites and Precambrian gneisses is recorded. Entisols, which are thin in depth, are the most common in these HUGs. Climatic characteristics are responsible for dividing this area into two homogeneous units of geodiversity: the Lowered Surface with a Mild Semi-Arid Climate and the Lowered Surface With a Moderate to strong Semi-Arid Climate. The first unit is situated in the eastern and northern sectors of the Chapada do Araripe, where the influence of the relief contributes to increased rainfall, with a dry season lasting up to 6 months. The second unit, however, has a dry season of 7 to 8 months, with some sectors in the southern part of the plateau experiencing up to 10 months of dry weather.

Semi-Arid Crystalline Massifs: these are residual landforms that stand out in the hinterland, formed by Precambrian granitoid bodies that were exhumed by differential erosion and remain in

the landscape due to semi-arid climatic conditions. Located in the northern part of the study area, it is observed that the massifs are structured under the strong influence of faults with a predominantly south-west to north-east orientation, coinciding with the direction of the lineament of shear zones and rifts that formed during the Brazilian Cycle.

Semi-Arid River Plains: these are areas of sediment accumulation that form in the valleys of intermittent rivers. The relief is flat and the sediments originate on the slopes, through mass movements, surface runoff and the action of the rivers themselves, which have considerable discharge potential, particularly during the rainy season between summer and autumn[29]. In these deposition zones, Fluvial Neosol is formed, which is extensively cultivated[26].

3.2 Geodiversity Ecosystems Services in the Chapada do Araripe and surrounding areas

The diversity of the abiotic environment in the study area offers benefits to society, as it supports different types of geodiversity ecosystem services (GES). These services have been identified and are distributed across the HUGs, as shown in Table 5.

Table 5. - Geodiversity ecosystem services present in Chapada do Araripe and adjacent areas.

	CATEGORIES / BENEFITS	HUGs								
		Sub-Humid Plateau	**Semi-Arid Plateau**	**Sub-Humid Slope**	**Semi-Arid Slope**	**Peripheral Lowered Surface**	**Lowered Surface With a Mild Semi-Arid Climate**	**Lowered Surface With a Moderate To Severe Semi-Arid Climate**	**Semi-Arid Crystalline Massifs**	**Semi-Arid River Plains**
REGULATION	1.1 Climate and Air Quality Regulation	Present (A, B, C, E)	Present (A, B, C, E)	Present (A, B, C, E)	Absent	Absent	Absent	Absent	Absent	Absent
	1.2 Atmospheric and/or Oceanic Regulation	Present (A, B, C, E)	Absent	Present (A, B, C, E)	Absent	Absent	Absent	Absent	Absent	Absent
	1.3 Water Regulation	Present (A, B, C)	Present (A, B, C)	Present (A, B, C)	Present (A, B, C)	Present (A, B, C)	Absent	Absent	Absent	Present (A, B, C)
	1.4. Water Quality/Water Purification and Waste Treatment	Present (B, C)	Present (B, C)	Present (B, C)	Absent	Absent	Absent	Absent	Absent	Present (B, C)
	1.5 Flood control	Present (A, B, C, D)	Present (A, B, C, D)	Present (A, B, C, D)	Present (A, B, C, D)	Absent	Absent	Absent	Absent	Present (A, B, C, D)
	1.6 Natural Risk and Erosion Control	Present (A, B, C)	Present (A, B, C)	Present (A, B, C)	Present (A, B, C)	Absent	Absent	Absent	Absent	Present (A, B, C)
	TOTAL	6	5	6	3	1	0	0	0	4
		Sub-Humid Plateau	**Semi-Arid Plateau**	**Sub-Humid Slope**	**Semi-Arid Slope**	**Peripheral Lowered Surface**	**Lowered Surface With a Mild Semi-Arid Climate**	**Lowered Surface With a Moderate To Severe Semi-Arid Climate**	**Semi-arid Crystalline Massifs**	**Semi-Arid River Plains**
SUPPLY	2.1 Freshwater supply	Present (A, B, C, D)	Present (A, B, C, D)	Present (A, B, C, D)	Present (A, B, C, D)	Present (A, B, C, D)	Present (A, B, C, D)	Present (A, B, C, D)	Absent	Present (A, B, C, D)
	2.2 Industrial materials	Present (A, B, D)	Absent	Absent	Present (A, B, D)	Present (A, B, D)	Present (A, B, D)	Present (A, B, D)	Absent	Absent

	2.3 Energy (renewable and non-renewable)	Absent	Present (A, D)	Present (A, D)	Absent	Present (A, D)	Present (A, D)	Present (A, D)	Absent	Absent
	2.4 Nutrients and minerals for healthy growth	Present (A, C, D)	Present (A, C, D)	Present (A, C, D)	Present (A, C, D)	Present (A, C, D)	Present (A, C, D)	Present (A, C, D)	Present (A, C, D)	Present (A, C, D)
	2.5 Ornamental features	Absent	Absent	Present (A, B)	Present (A, B)	Present (A, B)	Absent	Absent	Present (A, B)	Absent
	2.6 Construction materials	Present (A, D)	Present (A, D)	Present (A, D)	Present (A, D)	Present (A, D)	Present (A, D)	Present (A, D)	Present (A, D)	Present (A, D)
	TOTAL	4	4	5	5	6	5	5	3	3
	CATEGORIES / BENEFITS	**Sub-Humid Plateau**	**Semi-Arid Plateau**	**Sub-Humid Slopes**	**Semi-Arid Slopes**	**Peripheral Lowered Surface**	**Lowered Surface With a Mild Semi-Arid Climate**	**Lowered Surface With a Moderate To Severe Semi-Arid Climate**	**Semi-Arid Crystalline Massifs**	**Semi-Arid River Plains**
CULTURAL AND KNOWLEDGE	3.1 Cultural diversity	Absent	Present (A, B)	Present (A, B)	Present (A, B)	Present (A, B)	Present (A, B)	Present (A, B)	Present (A, B)	Present (A, B)
	3.2 Spiritual and religious values and cultural meanings	Present (A, B, D)	Present (A, B, D)	Present (A, B, D)	Present (A, B, D)	Present (A, B, D)	Present (A, B, D)	Present (A, B, D)	Present (A, B, D)	Absent
	3.3 Knowledge systems	Present (A, B)	Present (A, B)	Present (A, B)	Present (A, B)	Present (A, B)	Present (A, B)	Present (A, B)	Present (A, B)	Present (A, B)
	3.4. Education	Present (B)	Present (B)	Present (B)	Present (B)	Present (B)	Present (B)	Present (B)	Present (B)	Present (B)
	3.5 Artistic inspiration	Present (B)	Present (B)	Present (B)	Present (B)	Present (B)	Present (B)	Present (B)	Present (B)	Absent
	3.6 Aesthetics	Present (A, C, D)	Present (A, C, D)	Present (A, C, D)	Present (A, C, D)	Present (A, C, D)	Present (A, C, D)	Present (A, C, D)	Present (A, C, D)	Present (A, C, D)
	3.7 Social relations	Present (A, B)	Present (A, B)	Present (A, B)	Present (A, B)	Present (A, B)	Present (A, B)	Present (A, B)	Present (A, B)	Present (A, B)
	3.8 Sense of place	Present (A, B, D)	Present (A, B, D)	Present (A, B, D)	Present (A, B, D)	Present (A, B, D)	Present (A, B, D)	Present (A, B, D)	Present (A, B, D)	Absent
	3.9 Cultural Heritage and Geoheritage	Present (A, B)	Present (A, B)	Present (A, B)	Present (A, B)	Present (A, B)	Present (A, B)	Present (A, B)	Present (A, B)	Absent
	3.10 Health and well-being	Present (A, B, D)	Absent	Present (A, B, D)	Absent (A, B, D)	Absent	Absent	Absent	Absent	Present (A, B, D)

	3.11 Nature-based recreation and tourism	Present (A, B, D)	Present (A, B, D)	Present (A, B, D)	Absent	Present (A, B, D)	Present (A, B, D)	Present (A, B, D)	Present (A, B, D)	Present (A, B, D)
	TOTAL	10	10	11	9	10	10	10	10	7
	CATEGORIES / BENEFITS	**Sub-Humid Plateau**	**Semi-Arid Plateau**	**Sub-Humid Slopes**	**Semi-Arid Slopes**	**Peripheral Lowered Surface**	**Lowered Surface With a Mild Semi-Arid Climate**	**Lowered Surface With a Moderate To Severe Semi-Arid Climate**	**Semi-Arid Crystalline Massifs**	**Semi-Arid River Plains**
SUPPORT	4.1 Soil formation processes	Present (A, B, C)	Present (A, B, C)	Present (A, B, C)	Present (A, B, C)	Present (A, B, C)	Present (A, B, C)	Present (A, B, C)	Present (A, B, C)	Present (A, B, C)
	4.2 Burial and storage	Absent	Present (D)	Absent	Absent	Present (D)	Present (D)	Present (D)	Absent	Absent
	4.3 Platform for human activity	Present (A, B, C, D)	Present (A, B, C, D)	Present (A, B, C, D)	Absent	Present (A, B, C, D)	Present (A, B, C, D)	Present (A, B, C, D)	Present (A, B, C, D)	Present (A, B, C, D)
	4.4 Biogeochemical cycling	Present (A, B, C)	Present (A, B, C)	Present (A, B, C)	Present (A, B, C)	Present (A, B, C)	Present (A, B, C)	Present (A, B, C)	Present (A, B, C)	Present (A, B, C)
	4.5 Habitat Provision	Present (A, B)	Present (A, B)	Present (A, B)	Present (A, B)	Present (A, B)	Present (A, B)	Present (A, B)	Present (A, B)	Present (A, B)
	TOTAL	4	5	4	3	5	5	5	4	4
TOTAIS FINAIS		24	24	26	20	22	20	20	17	18

Legend: A – Fieldwork; B – Bibliographies; C – Cartographic survey; D – Satellite image analysis; E - Data collection from government agencies;

The GES vary according to the HUG. Table 6 presents the valuation according to the degree of relevance of each category of geodiversity ecosystem services that were assessed in each unit of the study area.

Table 6. Valuation of the relevance of GES.

GES Categories	HUGs	Score assigned	Degree of relevance	Relevance capacity
Regulatory Services	Sub-Humid Slope	100 %	5	Very high
	Semi-Arid Plateau	83%	4	High
	Sub-Humid Plateau	100%	5	Very high
	Peripheral Lowered Surface	17%	1	Very low
	Semi-Arid Slope	50%	3	Medium
	Lowered Surface With a Mild Semi-Arid Climate	0%	0	Not relevant
	Lowered Surface With a Moderate To Severe Semi-Arid Climate	0%	0	Not relevant
	Semi-Arid River Plains	67%	3	Medium
	Semi-Arid Crystalline Massifs	0%	0	Not relevant
Provisioning services	Sub-Humid Slopes	83%	4	High
	Semi-Arid Plateau	67%	3	Medium
	Sub-Humid Plateau	67%	3	Average

	Peripheral Lowered Surface	100%	5	Very high
	Semi-arid Slopes	83%	4	High
	Lowered Surface With a Mild Semi-Arid Climate	83%	4	High
	Lowered Surface With a Moderate To Severe Semi-Arid Climate	83%	4	High
	Semi-arid River Plains	50%	2	Low
	Semi-Arid Crystalline Massifs	50%	2	Low
Cultural and Knowledge Services	Sub-Humid Slope	100%	5	Very high
	Semi-Arid Plateau	91%	5	Very high
	Sub-Humid Plateau	91%	5	Very high
	Peripheral Lowered Surface	91%	5	Very high
	Semi-Arid Slope	81%	4	High
	Lowered Surface With a Mild Semi-Arid Climate	91%	5	Very high
	Lowered Surface With a Moderate To Severe Semi-Arid Climate	91%	5	Very high
	Semi-arid River Plains	64%	3	Medium
	Semi-Arid Crystalline Massifs	91%	5	Very high

Support Services	Sub-humid Slopes	80%	4	High
	Semi-arid Plateau	100%	5	Very high
	Sub-humid Plateau	80%	4	High
	Peripheral Lowered Surface	100%	5	Very high
	Semi-arid Slope	60%	3	Medium
	Lowered Surface With a Mild Semi-Arid Climate	100%	5	Very high
	Lowered Surface With a Moderate To Severe Semi-Arid Climate	100%	5	Very high
	Semi-arid river plains	80%	4	High
	Crystalline Massifs Semi-arid	80%	4	High

In turn, Table 7 presents the overall valuation of all GES in the study area.

Table 7. Overall valuation of the relevance of GES.

	HUGs	Score assigned	Degree of relevance	Relevance capacity	Ranking
GES	Sub-Humid Slope	93%	5	Very high	1
	Semi-Arid Plateau	86%	4	High	2
	Sub-Humid Plateau	86%	4	High	2
	Peripheral Lowered Surface	79%	4	High	4
	Semi-arid Slope	71%	4	High	5
	Lowered Surface With a Mild Semi-Arid Climate	71%	4	High	5

	Lowered Surface With a Moderate To Severe Semi-Arid Climate	71%	4	High	5
	Semi-Arid River Plains	64%	3	Medium	8
	Semi-Arid Crystalline Massifs	61%	3	Medium	9

4. DISCUSSION

The common characteristics among the elements of geodiversity, particularly geology, geomorphology and climate, form the HUGs in the Chapada do Araripe and its adjacent areas. Geodiversity ecosystem services were identified across the study area, with their provision varying according to the physical and natural characteristics of each unit. The Sub-Humid Plateau exhibit distinctive natural features, particularly regarding soil, relief and climate, setting them apart from the other units identified and analysed. For this reason, this area are considered exceptional landscape.

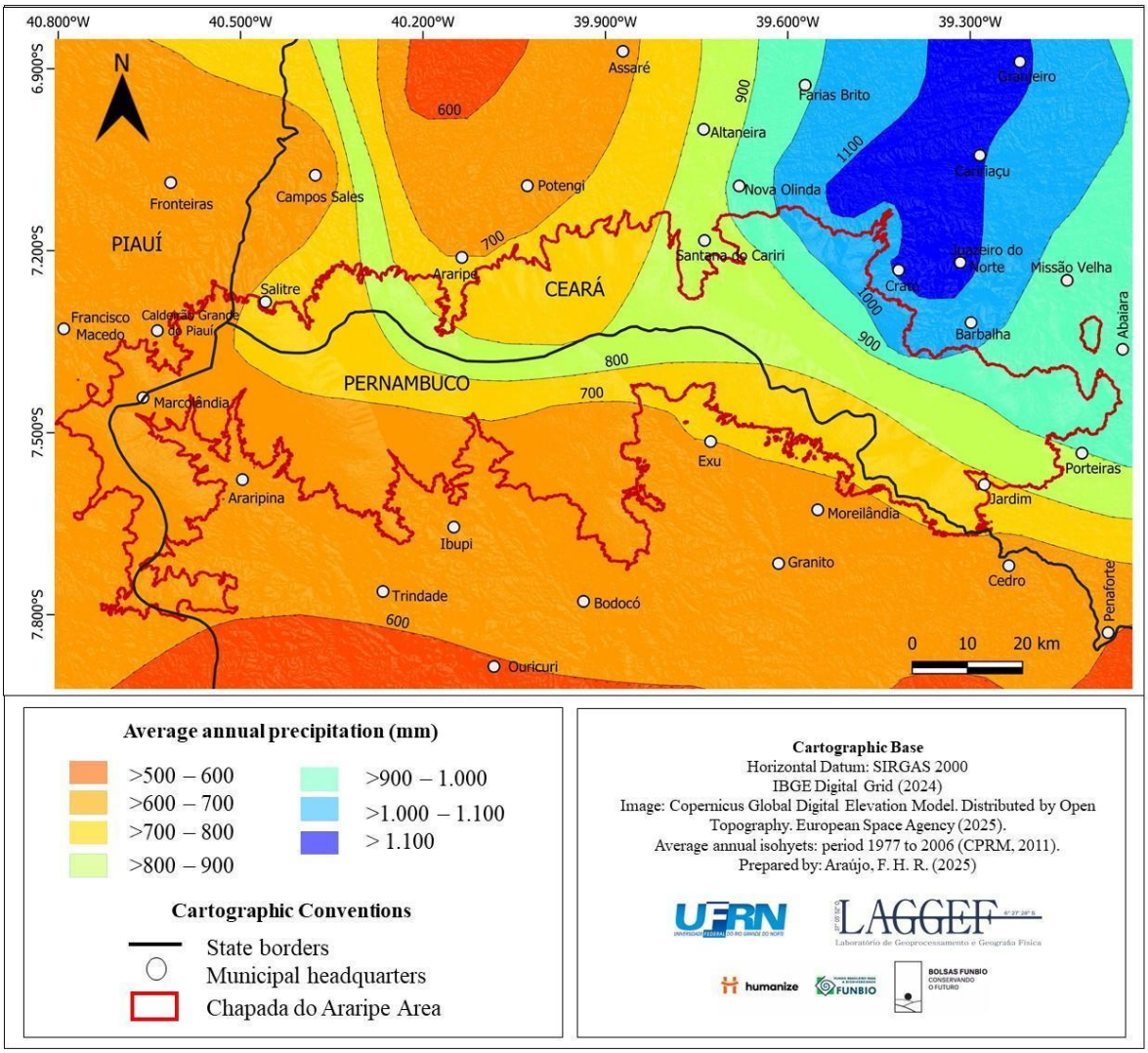
Exceptional landscapes provide more geodiversity ecosystem services than the surrounding landscapes, which is most evident in the provision of regulatory services. The Sub-Humid Slope and the Sub-Humid Plateau, however, are the only HUGs that provide all the benefits of the regulation service with the highest degree of relevance. In the other services, the exceptional landscapes do not differ as much from the others; nevertheless, the sub-humid slope has a high or very high relevance capacity across all services.

The relationship between relief, lithology and climate facilitates the formation of the exceptional landscape and contributes to a greater provision of regulation services, whilst the units forming the exceptional landscape achieved the highest degree of relevance for the ES provided by geodiversity.

The regulation of climate and air quality in the Chapada do Araripe is conditioned by the relief, which results in the formation of a microclimate with higher annual precipitation rates and lower average temperatures compared to the surrounding areas (Figure 7). The plateau is responsible for the formation of orographic rainfall, providing the direct benefits of 1.1 and 1.2 on the sub-humid plateau and the sub-humid slope (Figure 8). These two benefits were also identified, albeit indirectly, on the semi-arid plateau, which, despite having lower rainfall, has a topography that results in lower temperatures compared to adjacent areas. The exceptional landscapes were delineated by the presence of more humid vegetation in the case of the sub-humid HUGs, particularly the tropical forest found in the Araripe National Forest (Figure 9) and the Cerrado

vegetation (Semi-Arid Plateau). The delineation of the sub-humid exception units coincides, practically, to the east, west and south with the 900 mm/year isohyets (Figure 9).

Fig. 7: Average annual precipitation in Chapada do Araripe and adjacent areas.



Source: Araújo (2025).

Fig. 8: Climate and air quality regulation and atmospheric regulation in the Chapada do Araripe.

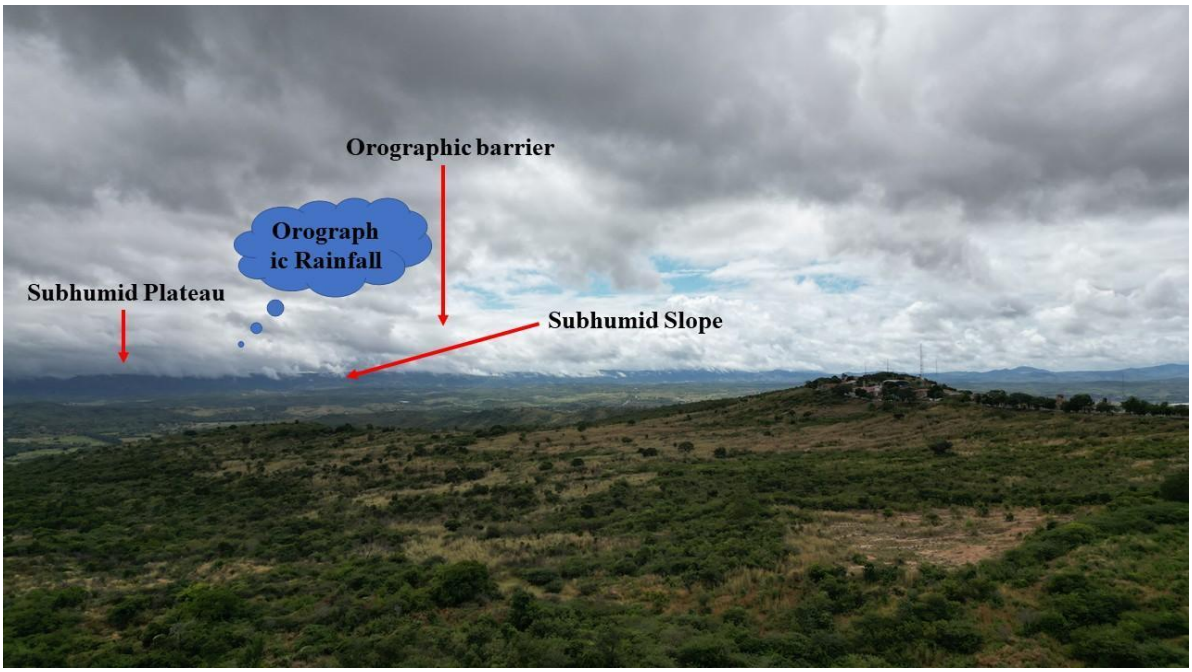
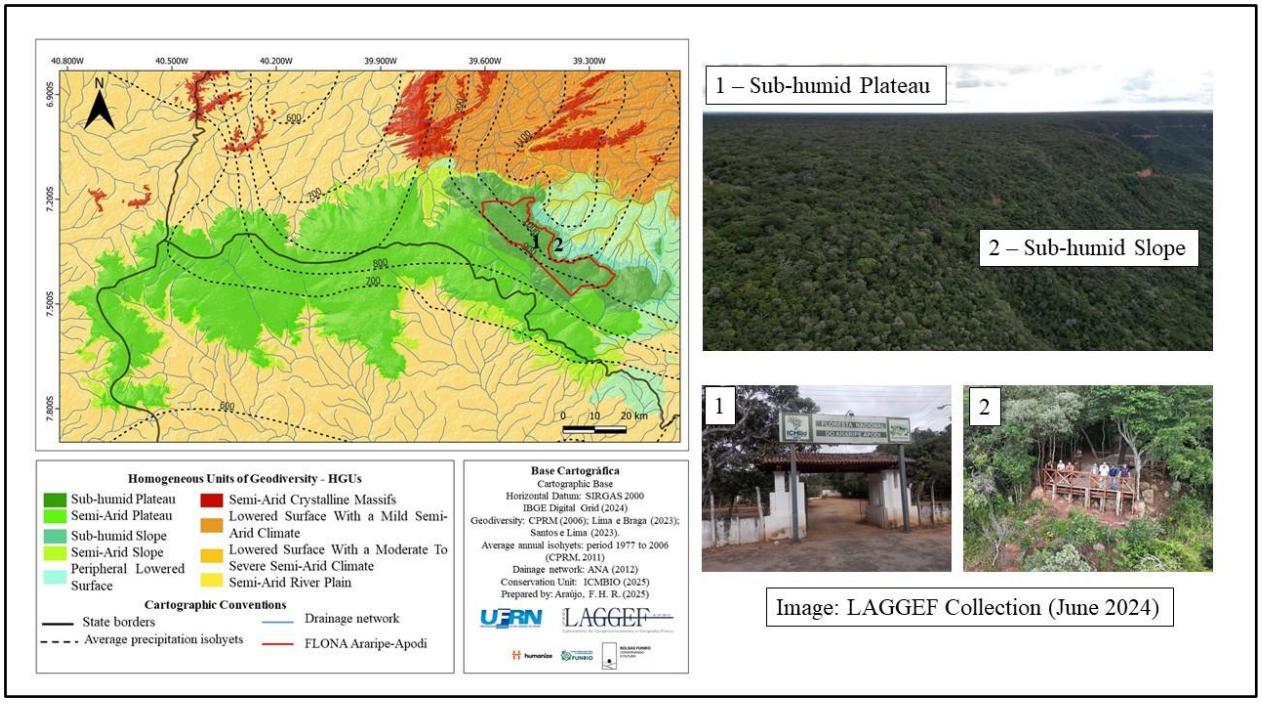


Fig. 9: Delimitation of the subhumid exception units and the Araripe National Forest.



Source: LAGGEF Collection, 2024.

The high porosity of the sedimentary rocks contributes to the direct provision of benefits 1.3, 1.4, 1.5 and 1.6. Both the subhumid and semi-arid parts of the plateau, covered by the Exu Formation, exhibit these characteristics. According to Dantas et al.[31], the summit of the Chapada do Araripe is an environment with high infiltration and an aquifer recharge zone. This is due to the high porosity of the rocks of the Exu Formation which, according to Lima et al.[29], does not favour surface runoff, contributing to the maintenance of the tableland's tabular form. These

characteristics ensure that water entering the aquifers is purified and that erosion-related impacts are mitigated. These benefits are also present in the areas covered by sedimentary deposits of the Santana Formation, which overlies the slope units. In sub-humid climate zones, the rainy season lasts around seven months a year, with an average of around five months of drought. However, the high porosity and permeability of the sub-humid plateau allow the streams that originate on the plateau to be perennial, without drying up completely at any time of the year.

The Peripheral Lowered Surface was assessed as having a very low level of relevance in terms of the provision of regulatory services. Only the provision of benefit 1.3 is observed, which corresponds to the regulation of freshwater, which is conditioned by the perennial springs that form on the Sub-Humid Slopes, enabling access to water in the Peripheral Lowered Surface. This HUG has high rainfall rates, which are due to its proximity to the orographic barrier of the plateau. According to Ribeiro[30], the increase in rainfall near the plateau is due to the orography influenced by the higher elevations in the area, which, in this case, occur on the Sub-Humid Slope.

The two units situated in the Sertaneja Surface did not have regulation services. The characteristics of the semi-arid climate, combined with the lithology consisting of crystalline rocks and shallow soils with low permeability, hinder the provision of this category of GES. These same characteristics are found in Semi-Arid Crystalline Massifs, where no benefits in this category have been recorded either.

Situated near the orographic barrier of the Chapada do Araripe, the Semi-Arid River Plains showed an average level of relevance in the provision of services. Only benefits 1.1 and 1.2 were not found in this unit. These plains are formed by rivers that have their sources on the sub-humid slopes of Araripe, contributing directly to water regulation and indirectly to climate regulation. The virtually flat topography of the terrain, the composition of unconsolidated sediments and the high porosity of the soils allow for water purification, improving its quality (item 1.3). Furthermore, they minimise the impacts of flooding and the risks of erosion, examples of benefits 1.5 and 1.6, respectively

With regard to provision services, the Peripheral Lowered Area stands out as the only one to offer all the benefits, consequently achieving the highest score in the assessment of relevance. Next come the sub-humid and semi-arid slopes and the two semi-arid low-lying areas, all of which have a high degree of relevance. Only four benefits were identified in the Sub-Humid Plateau and the Semi-Arid Plateau, which classifies them as having medium relevance. The Semi-Arid Massifs and river plains were assessed as having a medium degree of relevance.Water supply is identified in all units, except in the Semi-Arid Crystalline Massifs, where supply is compromised by the

characteristics of the crystalline lithology and the steepness of the terrain, which forms escarpments.

The flat topography and the porosity of the rocks covering the plateau contribute to the formation of aquifers. On the Sub-Humid Plateau, the supply is indirect, serving only to maintain the flow of the perennial springs found on the slopes. On the Semi-Arid Plateau, the supply is direct, and the water is used for human and animal consumption via artesian wells in the municipality of Marcolândia (Piauí State). The water that percolates through the Exu Formation feeds the aquifers, forming several perennial springs on the Sub-Humid Slope. These springs give rise to rivers that flow through the Peripheral Lowered Surface, forming the river plains and reaching the Lowered Surface Area With a Mild Semi-Arid Climate. In this way, the supply of this resource is guaranteed.

Another key aspect of the supply of provision services is the provision of benefit 2.2, which corresponds to the supply of industrial materials. The extraction of metallic minerals in the study area enhances the supply of this benefit. In their study of mining in the Cariri Metropolitan Region, Moura-Fé, Bastos and Nascimento[47] established a correlation between mining activity and lithology. These authors identified various mining processes in the crystalline massifs, notably the extraction of copper and iron ore in the Serra de São Pedro, in the municipality of Caririaçu, and of granite in the Serra do Juá and Colina do Horto, located in Crato and Juazeiro do Norte respectively. In the southern part, more precisely in the Lowered Surface With a Moderate To Severe Semi-Arid Climate, there are records of gypsum in the municipality of Bodocó (Pernambunco State).

In addition, the extraction of limestone from the Santana Formation for cement production has been recorded[46], with rocks outcrop on the slopes. Limestone is also used as an ornamental resource, an example of benefit 2.5. Of note is the exploitation of Pedra Cariri in the municipalities of Nova Olinda and Santana do Cariri, a type of sedimentary limestone used in construction as cladding and even in ornamental pieces (Figure 10).

Fig. 10: Extraction of Pedra Cariri limestone, on the Semi-Arid Slope, Nova Olinda-CE.



Source: The authors in fieldwork in 2025.

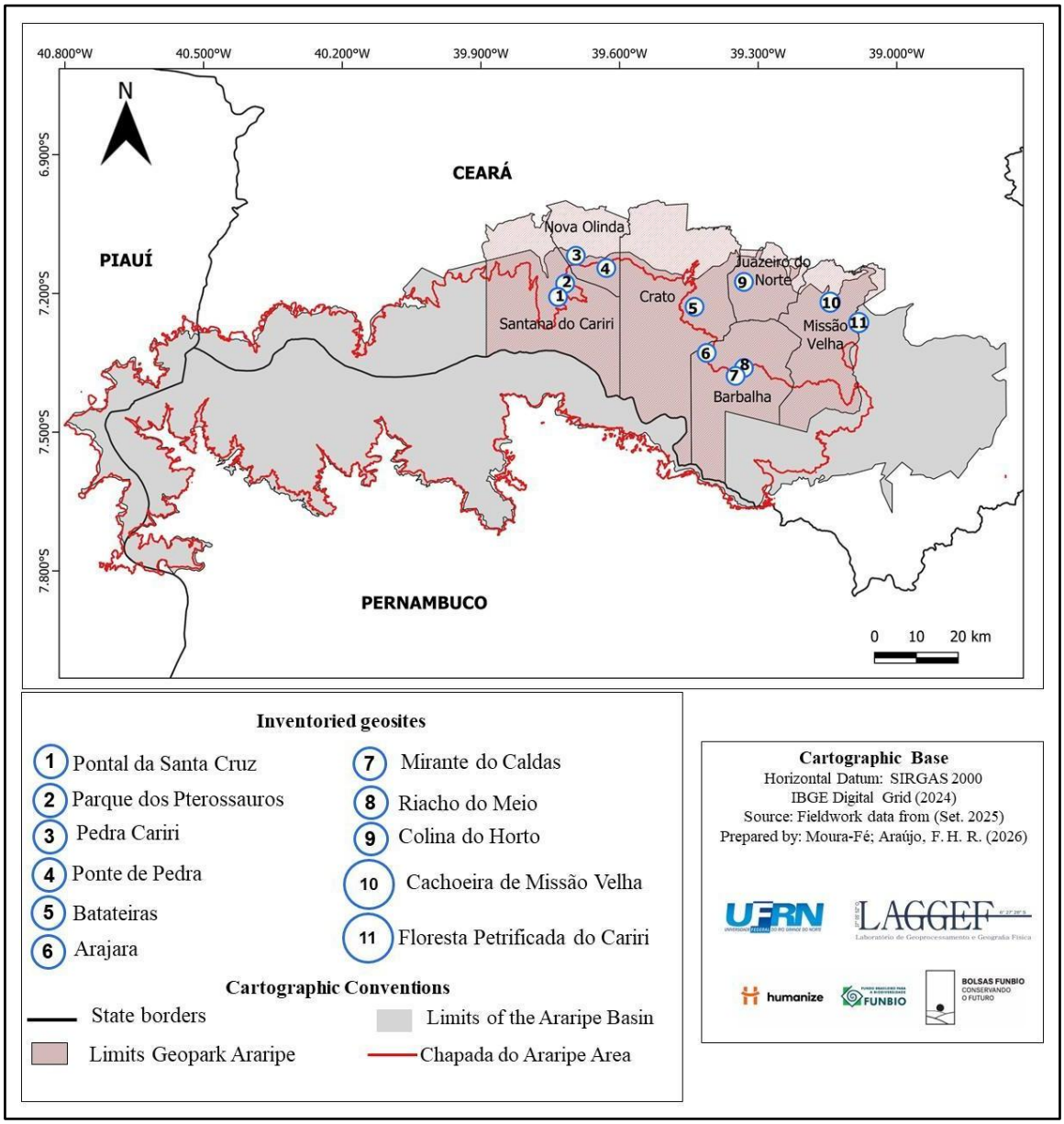
The energy supply, item 2.3, is most evident on the semi-arid plateau, which has wind turbines generating power. Also noteworthy is the production of solar energy via photovoltaic panels on the lower-lying areas, which benefit from the topography ranging from gentle to undulating and the hot climate with little rainfall. In the Peripheral Depression, the highlight is the Milagres Solar Complex, located in Abaiara, Ceará.

In all units of the study area, cultural services are the most prevalent, which highlights the region's cultural richness. Of note is the Sub-Humid Slope, which offers all the benefits and was rated as 'very high' in terms of relevance. The Sub-Humid Plateau, the Semi-Arid Plateau, the Peripheral Lowered Surface, the Semi-Arid Lowered Surface, the Lowered Surface with a Moderate to Severe Semi-Arid Climate and the Semi-Arid Crystalline Massifs were also assessed as having a 'very high' relevance score. The Semi-Arid Slopes were rated as having a high degree of relevance. The Semi-Arid River Plains, on the other hand, were rated as having a medium degree of relevance in terms of the provision of cultural services.

It is important to note that the study area overlaps with part of the Araripe Geopark, which has 11 inventoried geosites open to the public, highlighting the region's rich geoheritage (Figure 11). In addition to the geosites already assessed, the area's geodiversity allows for the expansion of the inventory. According to Moura-Fé[39], there are other sites of geological interest that have been identified but have not yet been fully inventoried. Owing to its natural and cultural value, the Chapada do Araripe was also nominated by Brazil for inclusion on the UNESCO World Heritage

List. These factors highlight the importance of the abiotic environment for the provision of item 3.9, relating to cultural heritage and geoheritage.

Fig. 11: Location of the inventoried geosites in the Araripe Geopark.



Source: Moura-Fé; Araújo (2026).

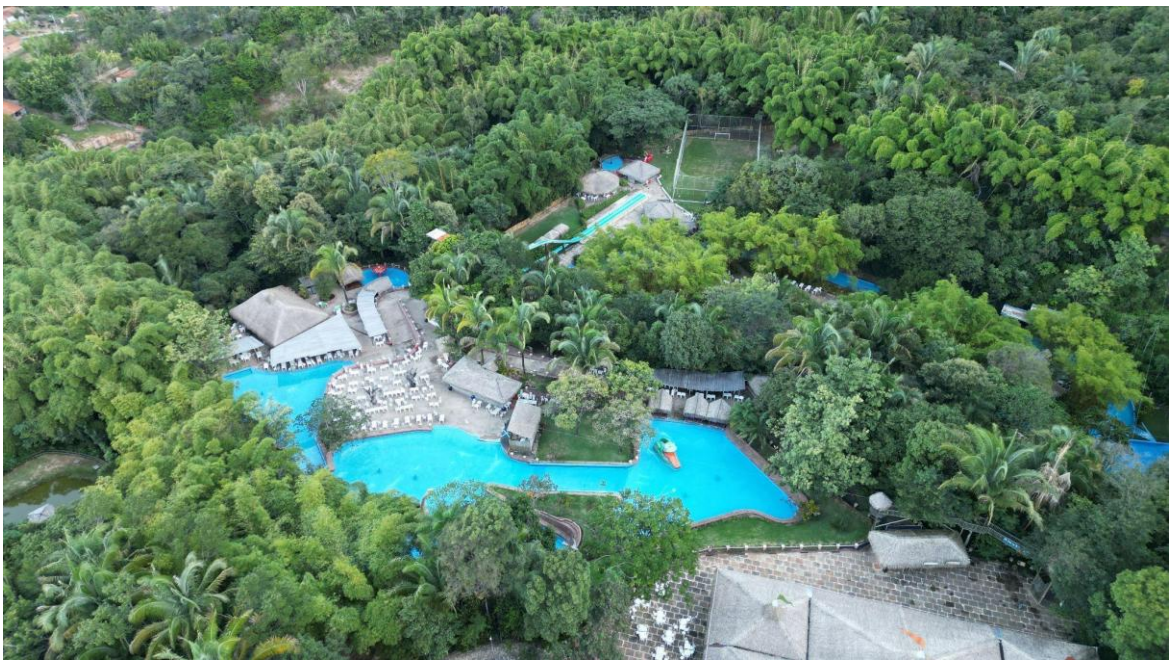
Benefit 3.1 was not identified on the Sub-Humid Plateau, whilst the Semi-Arid Plateau exhibits all the benefits. Spiritual and religious values are found in both units, exemplified by the Cruzeiro do Bom Jesus do Caldas, in the district of Caldas, Barbalha (Ceará State), and the Pontal de Santa Cruz, at the geosite of the same name, in Santana do Cariri (Ceará State).

Both sites offer locations conducive to understanding their formative processes, and their physical characteristics enable an understanding of the Earth's natural history, thereby providing essential resources for knowledge and education systems (benefits 3.3 and 3.4, respectively). The

area's natural features serve as artistic inspiration, contribute to people's well-being and enable nature-based recreation. This latter benefit is enhanced at the Mirante do Caldas geosite, in the municipality of Barbalha (Ceará State), where a cable car has been built to boost environmental and sustainable tourism in the region.

All cultural services were found on the sub-humid slope. Of note is the presence of inventoried geosites, such as Batateiras (Crato), Arajara, Mirante do Caldas and Riacho do Meio, all in the municipality of Barbalha (Ceará State). The provision of benefits 3.7, 3.10 and 3.11 is also clear. This area has several perennial springs, which form small watercourses and are used for leisure, health, well-being and nature-based recreation. In one of these watercourses, Arajara Park was built, a water park located in the district of Arajara which is very popular (Figure 12). Also noteworthy are the Caldas hydro-mineral spa, situated near the Mirante do Caldas geosite, and the crystal-clear waterfalls, nature trails, spouts and natural pools of the Riacho do Meio, which also provide the benefits.

Fig. 12 - View of Arajara Park, Arajara District.



Source: fieldwork in 2025

Item 3.11, nature-based recreation and tourism, was not found on the semi-arid slope. The rugged terrain and semi-arid conditions explain the absence of this benefit. The other benefits are identified, notably natural diversity, a sense of place and the artistic inspiration of the 'pé de serra' (foothills), which served as inspiration for one of singer Luiz Gonzaga's songs. Benefit 3.9, relating to geoheritage, is present in this area, as there are records of geosites such as the Ponte de Pedra in Nova Olinda (CE) and the Parque dos Pterossauros in Santana do Cariri (CE). In the latter

municipality, the Plácido Cidade Nuvens Museum of Palaeontology also stands out, featuring an exhibition of fossils collected in the Araripe- Basin. The museum provides access to knowledge systems and facilitates field trips for all levels of education (benefits 3.3 and 3.4).

Ten cultural services were identified in the Peripheral Lowered Surface, which is the area of the study that has a strong cultural appeal. The Cachoeira de Missão Velha geosite, which highlights benefit 3.9 related to geoheritage, and some natural pools provide the services listed under items 3.7 and 3.11.

The two units situated in the Sertaneja Surface offer all cultural services, except for item 3.10, which relates to people's health and well-being. Various benefits are offered, such as the system of knowledge and education demonstrated in the opportunities to acquire knowledge from the physical characteristics of the environment. A sense of place is deeply rooted in the inhabitants of these units, particularly regarding a sense of belonging to the "sertão" (hinterland), whose natural characteristics are most clearly evident. Special mention should be made of the Lowered Areas With a Moderate To Severe Semi-Arid Climate, particularly the Exu hinterland, where the scorching earth, high temperatures and lack of rain are highlighted in the song 'Asa Branca' by Luiz Gonzaga, a symbol of the Brazilian semi-arid region. The natural features of this homogeneous unit of geodiversity served as inspiration for several songs by Luiz Gonzaga, who was born in the municipality of Exu (PE) (Figure 13). Luiz Gonzaga is one of the greatest artists in Brazilian history – official sources report 56 albums recorded with over 500 songs and tens of millions of records sold – and is a native of the foothills of the Araripe on the Pernambuco side; the artist sang of the Araripe and the Cariri (as the region is known in the state of Ceará).

Fig. 13: The physical characteristics of the Exu Hinterlands served as artistic inspiration for Luiz Gonzaga, whose legacy has been preserved in the eponymous municipality.



Source: fieldwork in 2025

Cultural sites have also been identified in large numbers in the Semi-Arid Crystalline Massifs. Of note is Colina do Horto, an inselberg located in Juazeiro do Norte that is home to the religious monument of the statue of Padre Cícero, a key political and religious figure in the region's history (Figure 14), beatified by the Catholic Church and considered a 'popular saint'. Every year, this site, as well as the city of Juazeiro do Norte, welcomes millions of pilgrims in the name of faith and religious devotion. The pilgrimages to Juazeiro do Norte rank among the three largest in Brazil, alongside the Pilgrimage of Our Lady of Aparecida, patron saint of Brazil, and the Círio de Nazaré in Belém, in the state of Pará. Brazil is the largest Catholic country in the world, and the Blessed Padre Cícero is the "popular saint" who attracts the most faithful to his pilgrimage; the main one, the pilgrimage on All Souls' Day, attracts around 600,000 faithfuls, which is double the population of Juazeiro do Norte. The main place of worship is at the top of the inselberg, the Colina do Horto Geosite. This is a magnificent example of benefit 3.2. The religious monument serves as artistic inspiration, being depicted in various paintings and artworks. In addition to the viewpoint, which enhances benefit 3.6, there is the Santo Sepulcro trail, which features a variety of elements of geodiversity, contributing to the knowledge and education system (benefits 3.3 and 3.4).

Fig. 14: Statue of Padre Cícero at the Colina do Horto Geosite.



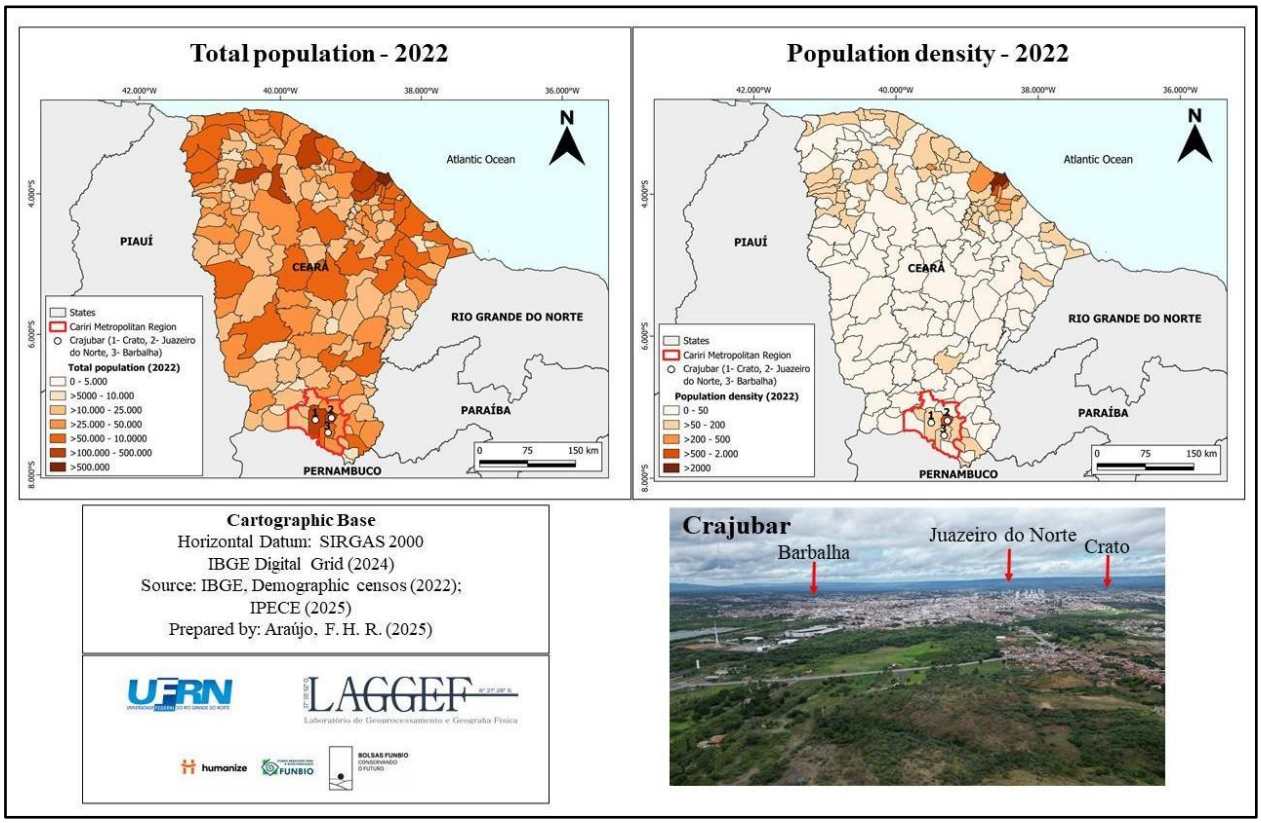
Source: fieldwork in 2025

Seven cultural benefits were identified in the semi-arid river plains, the vast majority of which are provided indirectly. The presence of water facilitates, in some cases, social interactions and succinctly highlights the aesthetic value during the rainy season, which is not necessarily spectacular. The only direct benefit relates to item 3.4, where the presence of rivers, combined with the flat topography and sandy soil, provides an example that can be used for educational purposes.

The HUGs assessed as having a 'very high' level of relevance in terms of the provision of support services were: the Semi-Arid Plateau, the Peripheral Lowered Surface, the Lowered Surface with a Mild Semi-Arid Climate, the Lowered Surface with a Moderate to Severe Semi-Arid Climate, and the Semi-Arid River Plains. All the benefits were found in these units. Of particular note is the presence of towns located within these units, highlighting the provision of the elements listed in sections 4.2 and 4.3, relating to burial, storage and platforms for human activities. On the flat terrain of the Semi-Arid Plateau lies the town of Marcolândia (PI), the only municipality whose administrative centre is situated on the summit of the plateau. The gently undulating terrain provides these benefits across both lowered surfaces. These characteristics, combined with the higher levels of humidity present due to the Araripe orographic barrier, result in a higher population density in the study area. It lies within the Peripheral Lowered Area, where the Crajubar region is situated—a conurbation comprising the municipalities of Crato, Juazeiro do

Norte and Barbalha. This region forms part of the Cariri Metropolitan Region (Figure 15), the largest urban agglomeration in the Brazilian semi-arid region, with around 600,000 inhabitants, alongside the regions of Petrolina (Pernambuco) and Juazeiro (Bahia), on the banks of the São Francisco River. There are more than 500,000 inhabitants in the three conurbated cities alone, with Juazeiro do Norte standing out; according to IBGE estimates for the population in 2025, it has already exceeded 300,000 inhabitants[48].

Fig. 15: Population data for the state of Ceará, with a focus on the Crajubar region.



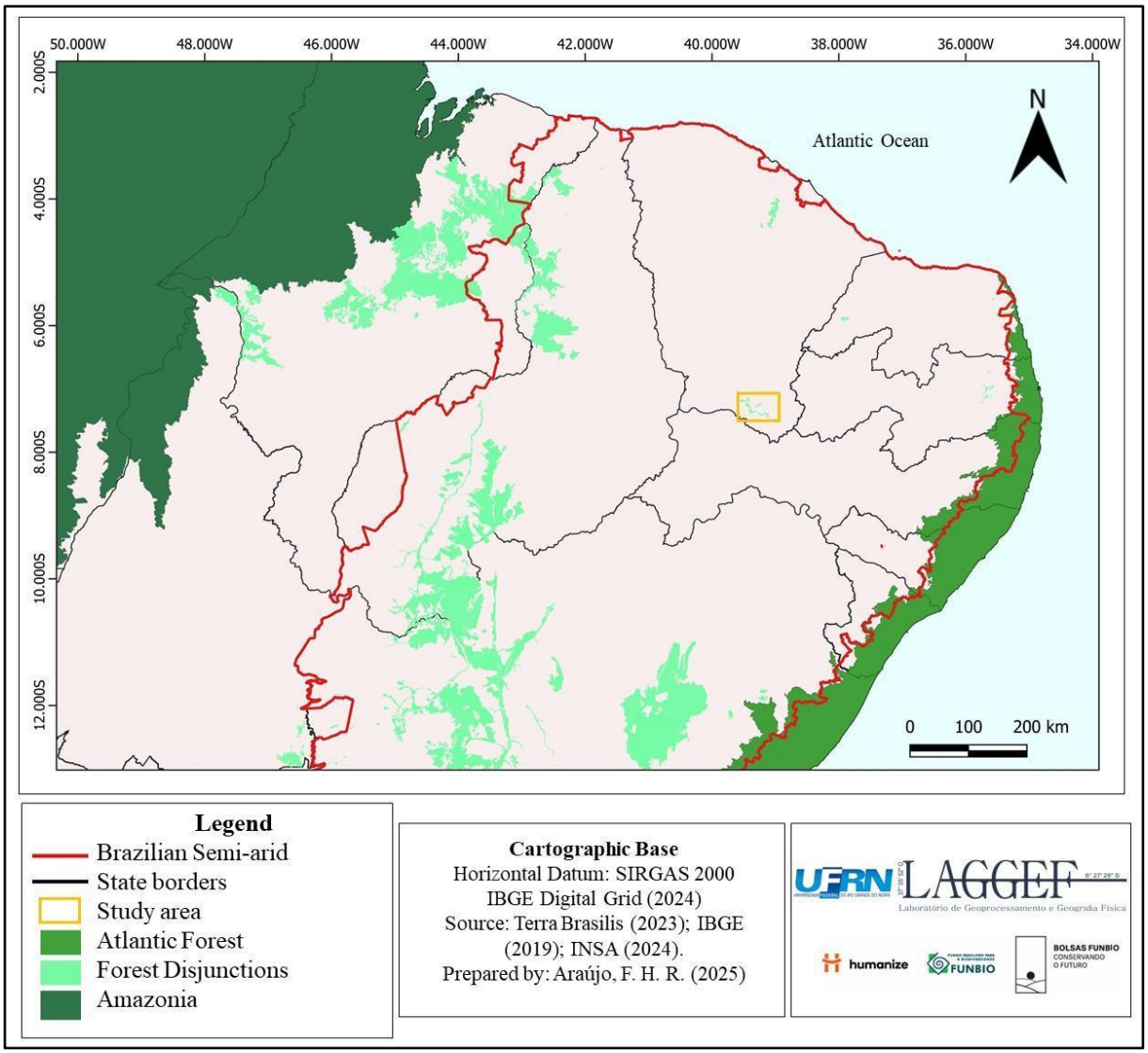
Source: authors.

The Sub-Humid Plateau was assessed as having a high degree of relevance in the support services category. Benefit 4.2, related to burial and storage, was not identified, given that a large part of this unit is located within the Araripe National Forest, which is a conservation unit belonging to the group of Sustainable Use Units[33]. Therefore, there are no landfill sites or cemeteries in the local communities where people live.

The greater presence of moisture on the Sub-Humid Plateau and Sub-Humid Slopes leads to the occurrence of patches of moist forests containing species from the Amazon and the Atlantic Forest (Figure 16). This demonstrates the role of geodiversity in maintaining and enhancing biodiversity with exceptional characteristics in these units. According to Araújo, Diniz and

Souza[16], geodiversity plays a fundamental role in providing geodiversity ecosystem services, which are essential for sustaining, regulating and maintaining these forest disjunctions.

Fig. 16: Atlantic humid forest disjunctions in Chapada do Araripe.



Source: authors.

In the perennial springs that form small watercourses on the sub-humid slopes, there is a species of freshwater crab, known as *Kingsleya attenboroughi*, which was discovered by Pinheiro and Santana[21] in watercourses near the district of Arajara, in the municipality of Barbalha (Ceará) (Figure 17). The animal is unknown to the local population and has no common name. This discovery supports the discussion on geodiversity and its contribution to heritage, particularly regarding the terrain and its relationship with the climate, which determine the conditions for the existence of habitats in the studied area. This crab has survived for thousands of years in the heart of the semi-arid hinterland because the relief of the Chapada do Araripe has created conditions for a humid microclimate, ensuring that these watercourses never dry up.

New discoveries of *Kingsleya attenboroughi* in other watercourses suggest that the crab's geographical distribution may be wider[49]. According to Nobre et al. [50], the occurrence of the species is associated with the vicinity of the headwaters of the Arajara, Cocos and Gameleiras streams, located on the subhumid slope of the Araripe, covered by patches of humid forest.

Fig. 17: The species *Kingsleya attenboroughi* Pinheiro & Santana, 2016 (freshwater crab) inhabiting the perennial springs of the subhumid slope of the Chapada do Araripe.



Source: fieldwork in 2025

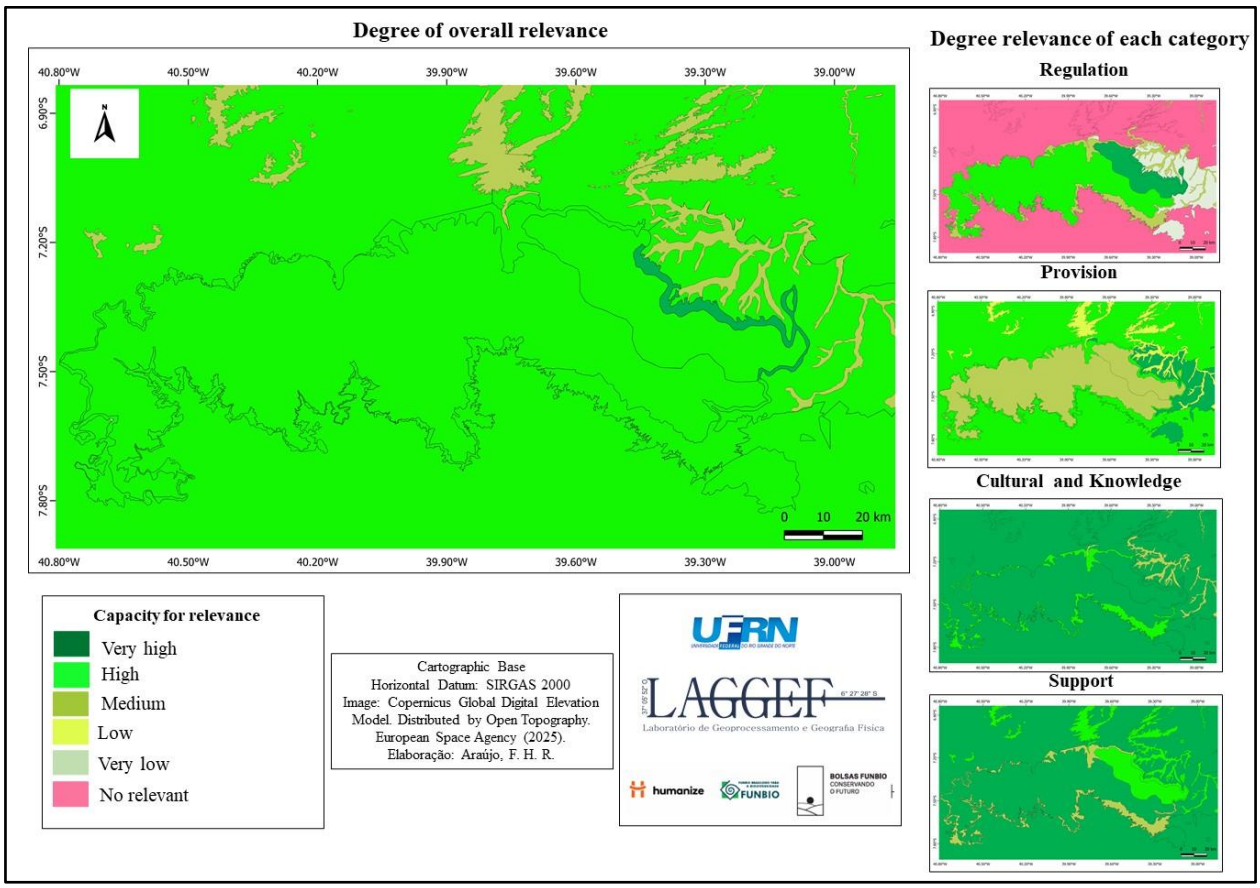
The terrain of the Araripe has maintained some perennial water sources over the last 11,000 years, even under a semi-arid climate with a dry season lasting six to eight months a year. The area of these springs is the habitat of the endemic species mentioned above. It is worth noting that if the springs where the specimens of *Kingsleya attenboroughi* live had dried up, even just once, over the last 11,000 years, the species would likely have become extinct. This represents a remarkable ecosystem service in a region where almost all rivers are intermittent.

The Semi-Arid Slope received an average rating for relevance, whilst the Sub-Humid Slope was rated as highly relevant . The terrain, consisting mainly of escarpments, hinders the provision of benefits 4.2 and 4.3. The latter, however, is recorded on the Sub-Humid Slope, as part of the city of Crato (CE) is situated within this unit, constituting an example of a platform for human activity (item 4.3). The formation of colluvial soils occurs in some parts, thus ensuring the provision of benefit 4.1, relating to soil formation processes. Benefits corresponding to biogeochemical cycling and habitat provision were also found. The latter are very evident on the Sub-Humid Slope, as already mentioned.

The Semi-Arid Crystalline Massifs and Semi-Arid River Plains scored highly in the assessment. The former unit presents four benefits that are provided directly by geodiversity. Of note is the use of some inselbergs for the installation of platforms that generate economic benefits for society, such as the cable car and the communication signal towers at Colina do Horto. In some massifs, the formation of lithic and regolithic entisols was observed, with the presence of vegetation and even agriculture.

In view of the above, it is evident that geodiversity plays an essential role in the provision of ES in the study area. To provide a better understanding of the assessment of the degree of relevance, Figure 18 shows the assessment of the degree of relevance of the GES in the HUGs within the study area.

Fig. 18: Capacity for relevance of each category of geodiversity ecosystem services in the HUG.



Source: Araújo (2025).

After assessing the capacity for relevance of geodiversity ecosystem services (GES) in the HUGs of the study area, it was observed that natural characteristics, particularly those influenced by the relationship between relief and climate, played a crucial role in providing benefits to society. The relationship between relief and climate determines the provision of ES, which can be observed

in the vicinity of the Araripe orographic barrier. Table 7 and Figure 18 show that the area to the north-east of the plateau, which blocks synoptic winds, provides the greatest quantity of ES to society, influencing both the biotic environment and society.

When analysing climate regulation, a higher average precipitation is observed on the Sub-Humid Slope. These characteristics also favour the provision of provisioning and supporting services. The Sub-Humid Slope was the only HUG classified as having very high relevance in the overall assessment. As for the supporting services offered in this unit, the importance of the abiotic environment as a support for biodiversity stands out, corroborating the assertion by Silva and Nascimento[51] that geodiversity is the basis for the development of life on Earth.

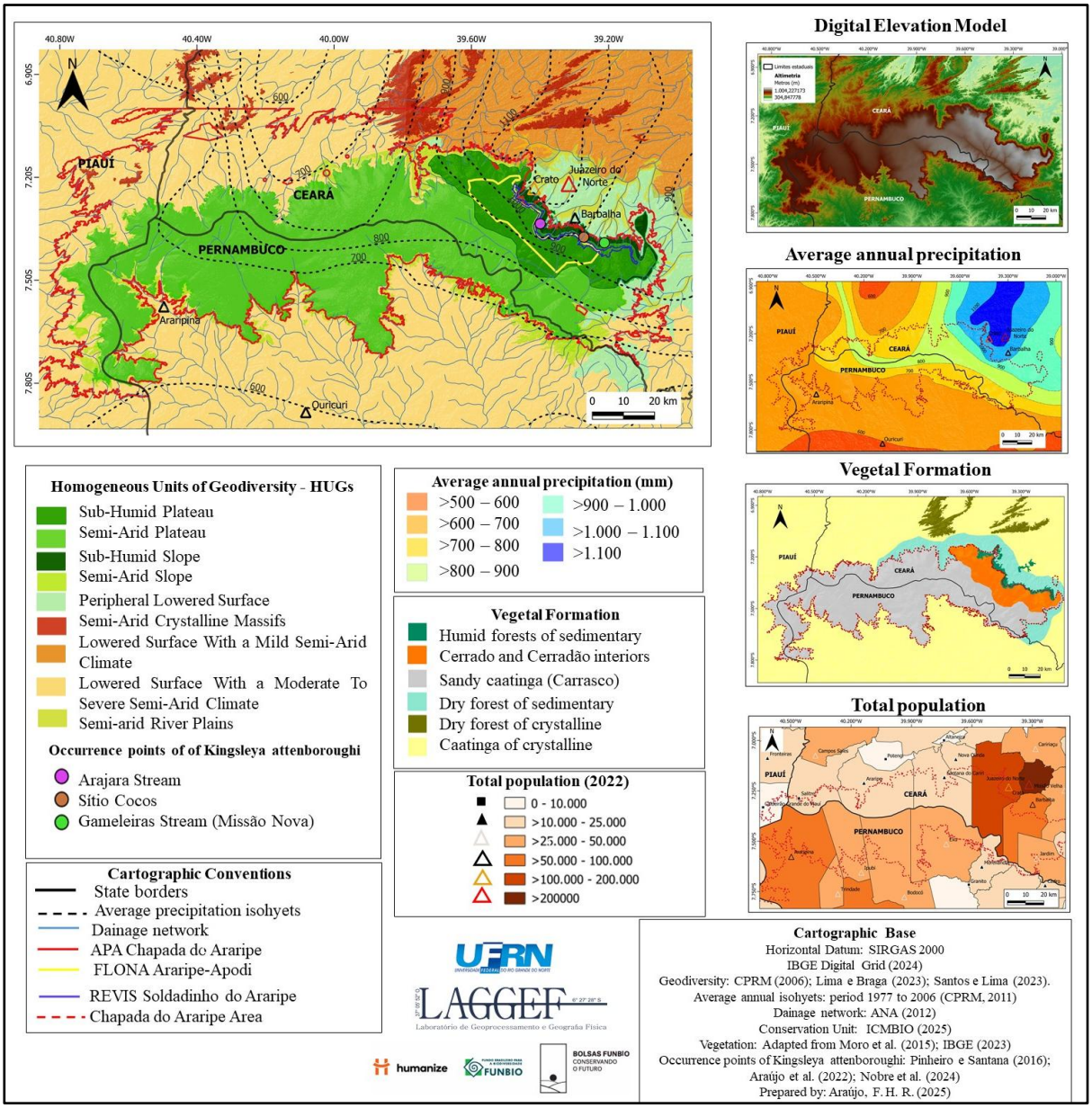
In addition, there is a rainforest containing elements of both the Atlantic Forest and the Amazon, where two endemic species have been recorded. According to Moro et al.[33], the humid forests are home to the Soldadinho do Araripe (*Antilophia bokermanni*), a bird of the genus Antilophia, and the freshwater crab *Kingsleya attenboroughi*. Three federal conservation units have been established in the region, two of which are specific to the wettest areas: the Araripe-Apodi National Forest (FLONA) and the Soldadinho do Araripe Wildlife Refuge (REVIS). The REVIS is a strictly protected area of great importance for the conservation of the Soldadinho do Araripe and *Kingsleya attenboroughi*, both of which depend entirely on the preservation of the springs for their survival. There is also the Chapada do Araripe Environmental Protection Area (APA), which covers the entire plateau. This environmental protection area requires close attention, as it suffers from deforestation and wildfires. According to Mourato and Rodrigues[52], the Chapada do Araripe APA ranks third among the most deforested areas in Brazil.

In the vicinity of the orographic barrier lies the highest population density in the entire Araripe region and the highest population density in the Brazilian semi-arid biome, which covers an area of approximately 800,000 km².

In the vicinity of the orographic barrier lies the highest population density in the entire Araripe region and the highest population density in the Brazilian Semi-Arid region. The Cariri region of Ceará owes its population density exclusively to the unique interplay between lithology, soil, topography, climate and hydrography, which has enabled the development of an extremely prosperous society in the midst of Brazil's poorest region – a veritable oasis in the Brazilian Semi-Arid region. The integrated map below shows how the relationship between topography and climate primarily determines the availability of resources in the study area (Figure 19). The Cariri region of Ceará, located in the north-east of the map, has the highest number of protected areas, is home to a UNESCO Geopark and has the highest population density in the Brazilian semi-arid

region, as well as being a candidate for UNESCO World Heritage Site status due to its natural and cultural values.

Fig. 19: Interactive map of the physical and natural characteristics of the Chapada do Araripe and adjacent areas.



Source: Araújo (2025).

The Subhumid slope is the most significant HUG, home to the animal species endemic to Araripe. The area largely coincides with the Soldadinho do Araripe Wildlife Refuge, a federal area of strict protection, given its extreme importance. The proposed method identified this area as being of the greatest significance. The rivers that supply the largest urban agglomeration in the Brazilian semi-arid region have their source within this HUG.

The evolution of the South American landscape, combined with local geological features, has transformed the Chapada do Araripe into an island of moisture within a semi-arid matrix. This characterises it as an exception to the regional pattern and provides a perfect setting for the story of life to be told in an exceptional way, featuring unique characters.

Alahuta, Toiavane and Hjort[53] wrote in the journal *Nature Ecology & Evolution* stating that the Geodiversity-Biodiversity relationship requires further empirical evidence, and Araripe provides much of it.

The geodiversity of the study area provides essential benefits that align with two SDG targets. The regulation of climate, air and water quality, as well as cultural, health and well-being benefits and nature-based recreation, contribute to SDG 3, which relates to the health and well-being of people of all ages. Meanwhile, conservation policies for the area, aligned with geoconservation strategies, contribute to the protection, restoration and promotion of the sustainable use of terrestrial ecosystems, aiming to achieve the target set out in SDG 15.

5. CONCLUSIONS

The interactions between geological, geomorphological and climatic elements form the HUGs, which exhibit similarities among the elements of geodiversity. In each of these units, geodiversity will provide ES that have been identified and assessed.

The study showed that the physical and natural characteristics of exceptional landscapes, influenced mainly by relief and climate, play a crucial role in providing benefits to society. It was found that sub-humid HUGs, under the direct influence of the Chapada do Araripe orographic barrier (mainly the Sub-Humid Slope), offer a greater range of services. The relationship between relief and climate determines the provision of ES in the study area, particularly regulation and geodiversity support services. Geodiversity supports the development of biodiversity, which is entirely dependent on the area's natural conditions and generates essential benefits aligned with SDGs 3 and 15.

When applying the method for assessing and classifying GES by category, it was observed that the units situated in the exceptional landscape, despite their natural peculiarities, did not show such clear differences in relation to the surrounding area. When analysed generally, the Sub-Humid Slope, a unit considered an exceptional landscape, is the one that provides the most services and the only one to be assessed as having a very high degree of relevance. The high level of cultural services meant that no HUG had low relevance. The replication of this study can serve as a basis

for further research at different spatial scales and in areas with natural conditions distinct from those of the study area.

Data availability

All data collected in this study are included in this paper.

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Conflicts of interest

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