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Abiotic Ecosystem Services in the Chapada Do Araripe, Unesco World Heritage Tentative Site

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ABIOTIC 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 (HGUs). The aim of the research was to identify the HGUs 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 HGUs, 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, 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" will be used.

To understand how geodiversity provides benefits to society, several proposals for assessing abiotic ES 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 abiotic 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 ES from geodiversity proposed by Araújo, Diniz and Souza[16].

Araújo, Diniz and Souza[16] developed their proposal by comparing the provision of ecosystem services supplied by geodiversity in different areas, following two stages: the qualitative stage, involving the identification and classification of ecosystem services; and the quantitative stage, involving the assessment of the degree of relevance of these services. This method was applied to the Martins-Portalegre plateaus in Rio Grande do Norte (Brazil) to compare the provision of abiotic ecosystem services in the geomorphological compartments of the plateaus—considered an exceptional landscape—with those of the adjacent areas.

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 ecosystem services (ES) due to geodiversity 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 Geodiversity Units (HGU), a proposal presented in this study. With the definition of HGUs, the method of Araújo, Diniz and Souza[16] can serve as a basis for the qualitative and quantitative assessment of the ES provided by geodiversity, 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 ES in each HGU. The aim is to understand and identify which sectors exhibit similarity in terms of geodiversity and how this is reflected in the provision of abiotic ES. The working hypothesis is that in the HGUs corresponding to the landscape of exception, there is a greater variety of geodiversity ES than in the dominant surrounding landscape.

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) Araripe Pygmy Antelope, Private Natural Heritage Reserves (RPPNs), and is a candidate for UNESCO World Heritage status due to its natural and cultural values[20]. Several endemic species are found in this region, the most famous being the Araripe soldierfly (*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].

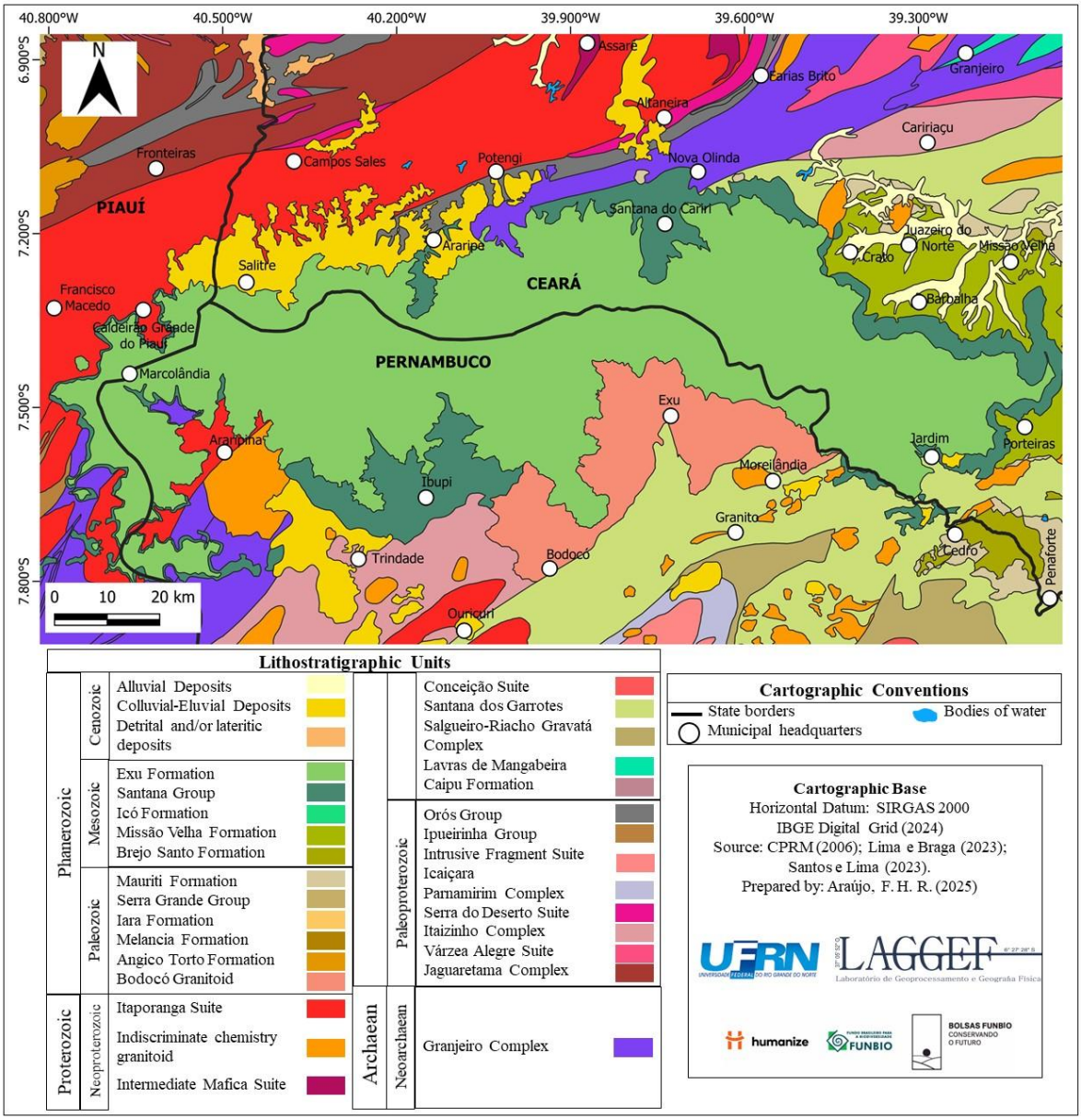
Applying the method for assessing the ecosystem services provided by geodiversity is essential to demonstrate the importance of the study area. The study contributes to the promotion of geoconservation and is aligned with two Sustainable Development Goals (SDGs): Goal 3, which aims to ensure healthy 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 study area corresponds to the Chapada do Araripe and its surroundings, 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).

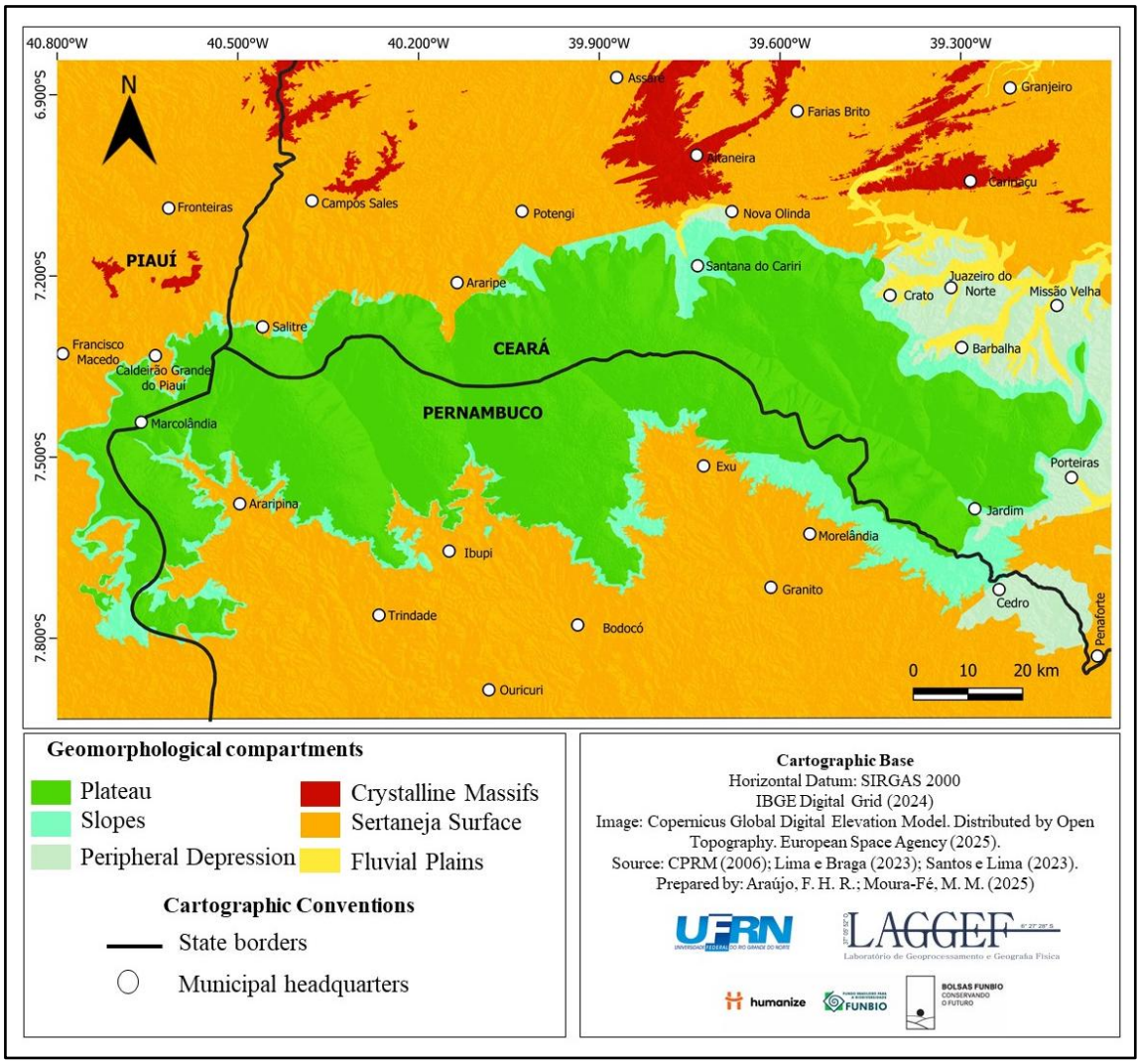
Fig. 1: Geology and Location of the Study Area.



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, Peripheral Depression, Crystalline Massifs, Sertaneja Surface and Fluvial Plains (Figure 2).

Fig. 2: Geomorphological compartments of the study area.



Source: Araújo; Moura-Fé (2025).

The plateau, slopes and peripheral depression 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 Peripheral Depression, 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 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

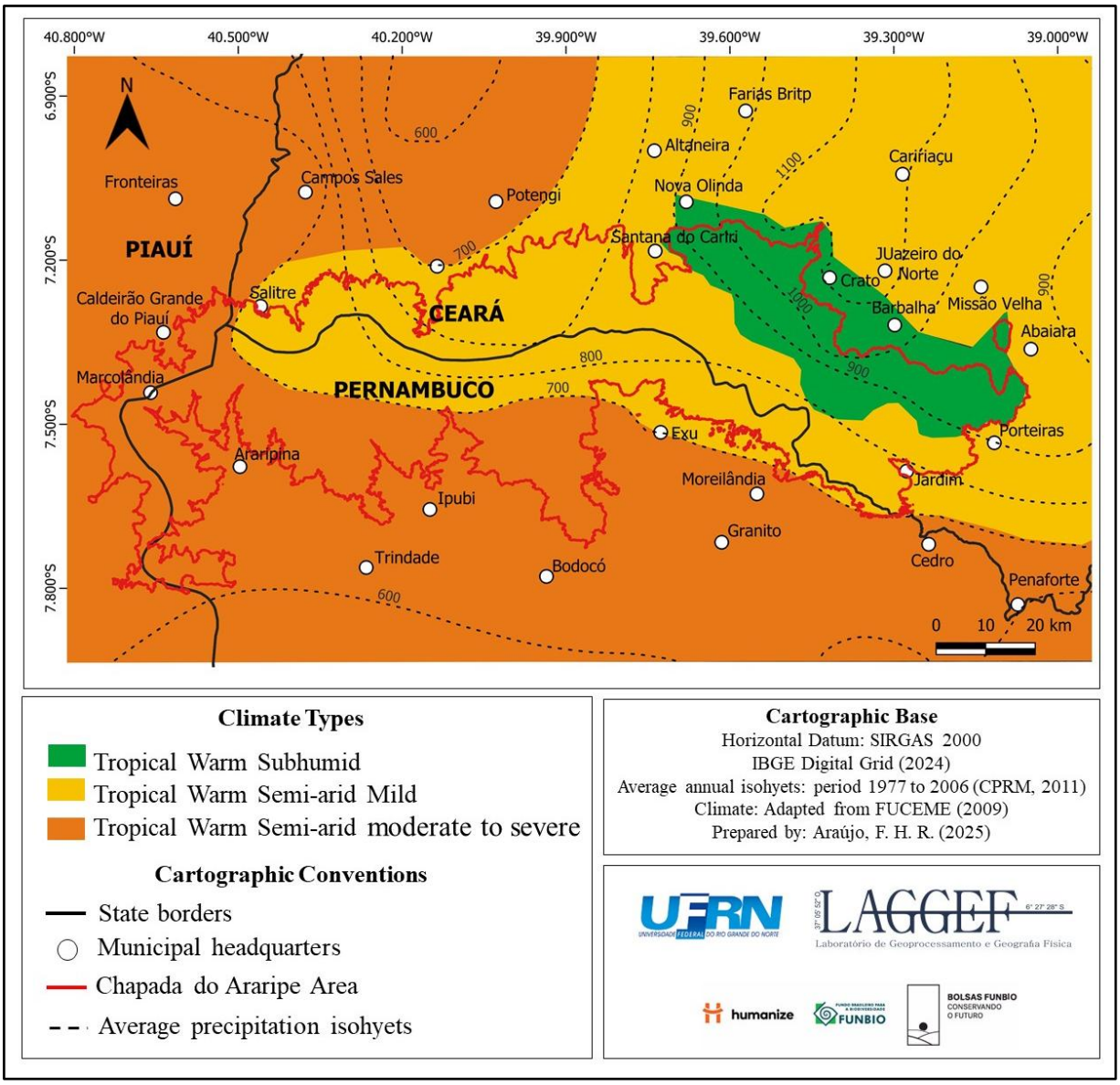
processes, associated with the resistance of their constituent material. These massifs correspond to residual landforms with steep escarpments and an area exceeding 50 km²[27].

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 Latossols and Argisols are found, alongside poorly developed soils such as Neossols[29]. Latossols predominate in the Exu and Missão Velha formations; Argissols develop on the sedimentary rocks of the Santana and Mauriti formations, as well as on some metamorphic rocks of the basement; and Neossols 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[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).

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 HGU 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*, *Scopus* and Google Scholar, with searches on the topics "Geomorphology" and "Araripe" to characterise the study area, and on the themes of "geodiversity" and "abiotic ecosystem services".

Among the cartographic materials, maps of geology, geomorphology and homogeneous geodiversity units 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 aforementioned 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 (HGUs), with HGUs 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.

The classification of geodiversity ecosystem services was based on field data collection using a form adapted by Araújo, Diniz and Souza[16], which groups the benefits into four categories: regulation, provisioning, cultural and supporting (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	**DIRECT, INDIRECT OR ABSENT SUPPLY**
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.	**Direct**: The characteristics of the physical environment directly alter the climate and air quality, determining specific features such as lower temperatures and increased precipitation. Topography, in turn, can contribute to increased humidity and provide ventilation conditions that enhance thermal comfort. **Indirect**: The physical characteristics of the area exert a slight influence on the local climate, for example, when an element of geodiversity provides conditions that cause minor changes in temperature. **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.	**Direct**: The abiotic environment and associated geomorphological aspects play a decisive role in atmospheric and oceanic regulation. An example is when the terrain acts as an orographic barrier to air masses or when it facilitates their movement to areas further inland from the coast. **Indirect:** It has some influence on atmospheric circulation and, consequently, on the climate, habitats and living conditions. **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.	**Direct**: When there is a contribution to the mitigation of natural risks, water quality, the supply of drinking water, the provision of habitats and opportunities for *on-site* recreation. **Indirect:** When the contribution is *ex situ*. For example, when there is recharge of an aquifer or river springs in an area, such that access to water is only available in the immediate vicinity. **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.	**Direct**: Economic benefits through reduced subsequent requirements for water supply treatment. **Indirect**: 'Cleaner' water for groundwater aquifers and surface water bodies and their dependent habitats. **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.	**Direct**: The characteristics of the abiotic environment play a key role in reducing the impacts of flooding, for example an area with porous sedimentary material. **Indirect**: It has a slight influence on reducing the impacts of flooding, sharing this function with the biotic environment. An example is leaf litter, a biotic soil material that aids in flood control 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.	**Direct:** when the abiotic environment contributes to: • Regulation of river flooding through natural defences against flooding and natural floodplains and/or anthropogenic excavations (such as quarries); • Protection against erosion of rivers and floodplains and protection against 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 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 against slope and soil erosion and risk assessment through analysis of rock and soil properties, slope stability and past 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	**DIRECT, INDIRECT OR ABSENT SUPPLY**
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.	**Direct**: Natural sources of fresh water, surface or groundwater, and mineral water. Abstraction of surface or groundwater for public supply, industrial supply or private domestic supply. **Indirect:** A source 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.	**Direct:** Resources used in industry are extracted in the area. One example is the mining of metallic ores. **Indirect:** There is incipient exploitation 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.).	**Direct**: The abiotic environment directly provides a high potential for the supply of energy resources. **Indirect**: The abiotic environment provides the basis for energy exploitation, albeit with limited potential. **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.	**Direct:** Soil type, combined with specific mineralogical characteristics, are determining factors for the growth or production of a particular activity. **Indirect:** Soil characteristics influence certain activities. An example is soil with low fertility, yet which allows for activities that do not determine the land's use. **Absent**: There are no such relationships.
2.5 Ornamental resources – Supply of rocks, fossils, minerals and aggregates for decoration and landscaping.	**Direct:** Where the area involves 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. **Indirect:** When there is no exploitation for economic purposes, but only for ornamentation, carried out in a traditional manner, using minerals or rocks. **Absent**: There are no such relationships.
2.6 Construction materials – Extraction of rocks, sediments and other materials for civil construction.	**Direct**: The extraction of essential inputs for civil construction takes place: sediments, rocks, sand and other minerals. **Indirect**: Materials linked to the construction industry are extracted for its operations. Example: 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	DIRECT, INDIRECT OR ABSENT SUPPLY

3.1 Cultural diversity – The diversity of the physical environment is a factor that influences cultural diversity and cultural identity.	**Direct:** The cultural diversity of a place is directly related to its geodiversity (churches and towns carved into the rock, for example). **Indirect**: The physical environment has a slight influence on local cultural characteristics (e.g. when cuisine relates to 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.	**Direct**: There is a strong relationship between the physical environment and local spiritual, religious and cultural values, extending beyond municipal boundaries. An example of this is when a shrine is revered by local residents and people from other areas. **Indirect**: There is a relationship between the physical environment and spiritual, religious and cultural values, limited solely to local residents. **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.	**Direct**: Environmental features serve as a good example and provide fundamental input for knowledge systems. For example, when an area of interest contains elements that act as baselines for understanding various evolutionary processes in Earth's history, climate change, and other phenomena. **Indirect**: Environmental characteristics provide support for knowledge systems. An example is when an element of geodiversity is used to assist in scientific research. **Not applicable**: 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 features provide a good example and can be used for education at all levels: primary, secondary and higher education. **Indirect**: Environmental features provide examples and can be used only in higher education. **Absent**: There are no links.
3.5 Artistic inspiration - Geodiversity provides a rich source of inspiration for art, literature, poetry, music, sculpture, national symbols, architecture, built heritage and gardens.	**Direct**: There are bibliographies, evidence and accounts that geodiversity has been a source of inspiration. **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.	**Direct**: Aesthetically rich and pleasing landscape characterised by the presence of at least two of the following features: ● Contrast of colours (with at least 3 colours); ● Vertical relief (>50 metres); ● Presence of bodies of water. **Indirect**: A landscape that stands out for just one of the above features, though it is not necessarily spectacular. **Absent:** Does not feature any of the characteristics.
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.	**Direct**: Ecosystem services play a fundamental role in the functioning of the local community. For example, an element of geodiversity directly affects the social relations of a community (a watercourse shapes a fishing community, a mineral shapes a mining community, etc.). **Indirect**: In some cases, ecosystem services enable social interactions based on an abiotic element. **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.	**Direct**: The physical characteristics of the area are appreciated by residents who attribute a sense of place to it. **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.	**Direct**: The area contains inventoried sites that are relevant to more than one Geoheritage parameter (Geological, Geomorphological, Pedological, Speleological, Hydrological, among others) and/or is strongly associated with local cultural identity. **Indirect**: The area contains inventoried sites that are relevant only to a specific parameter or sites of geodiversity interest. **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.	**Direct**: The area possesses physical and natural features that play a decisive role in people's well-being and health. Some examples include: the sounds of nature, thermal springs with therapeutic properties, and the contemplation of minerals, rocks or landforms. **Indirect**: Some areas possess physical and natural features that contribute to people's health and well-being during a specific period. For example, the sound of water from an intermittent waterfall. **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.	**Direct**: The area contains sites considered to be the main destinations for recreational activities for the local population and which usually receive some tourists. **Indirect**: The area contains sites that are commonly used for recreation and are partly frequented only by the local population. **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	DIRECT, INDIRECT OR ABSENT SUPPLY
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.	**Direct:** The abiotic environment favours pedogenesis, enabling the formation of well-developed soils. **Indirect:** Formation of poorly developed soils. **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.	**Direct:** Used 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).	**Direct:** Economic benefits arise from the platform provided by geodiversity, such as flat land for building towns and gorges or ravines for constructing dams. **Indirect:** Provides a basis for construction and infrastructure, without any economic benefits. **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.	**Direct:** Provision of minerals and nutrients necessary for the functioning of the biogeochemical cycle. **Absent:** There are no such relationships.
4.5 Habitat Provision – The physical environment generally plays a HGUe role in providing habitats for biodiversity, but this fact seems to be rarely recognised by ecologists.	**Direct:** The physical environment determines the characteristics of the habitat. For example, the terrain provides natural conditions for the development of endemic species. **Indirect:** The physical environment has a slight influence on the habitat of cosmopolitan species. For example, a cave that can be used as a habitat for bats. **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 ES, considering the number of benefits offered in each category.

However, Araújo, Diniz and Souza [16] quantified the relevance of the SE by considering only the number of services, disregarding whether their provision was direct or indirect. This article proposes the assignment of parameters to differentiate between direct and indirect provision.

Considering the number of classes proposed by Burkhard[45] (6 classes), 1.0 point was assigned for each direct benefit and 0.75 for each indirect benefit, where the maximum score for each category was divided by the number of classes. The equation used is presented below, with details in Table 2.

Regulatory services = 6.0/6

Provisioning services = 6.0/6;

Cultural and knowledge services = 11.0/6;

Supporting services = 5.0/6

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	6.0 points	0–0.99	0	Not relevant
			1 – 1.99	1	Very low
			2 – 2.99	2	Low
			3 – 3.99	3	Medium
			4 – 4.99	4	High
			5–6	5	Very high
Provision	6	6.0 points	0–0.99	0	Not relevant
			1 – 1.99	1	Very low
			2 – 2.99	2	Low
			3 – 3.99	3	Medium
			4 – 4.99	4	High

			5–6	5	Very high
Cultural and Knowledge	11	11.0 points	0 – 0.99	0	Not relevant
			1 – 2.99	1	Very low
			3 – 4.99	2	Low
			5 – 6.99	3	Medium
			7 – 8.99	4	High
			9–11	5	Very high
Support	5	5.0 points	0–0.80	0	Not relevant
			0.81 – 1.60	1	Very low
			1.61 – 2.40	2	Low
			2.41 – 3.20	3	Medium
			3.21 – 4.00	4	High
			4.10–5	5	Very high

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

The overall relevance of all geodiversity ecosystem services was also assessed. To this end, the maximum score was considered, which corresponds to the sum of the benefits across all categories, divided by the number of classes. Details are provided 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			0 – 4.99	0	Not relevant
			5 – 9.99	1	Very low

	28	28.0 points	10 – 14.99	2	Low
			15 – 19.99	3	Medium
			20 – 24.99	4	High
			25–28	5	Very high

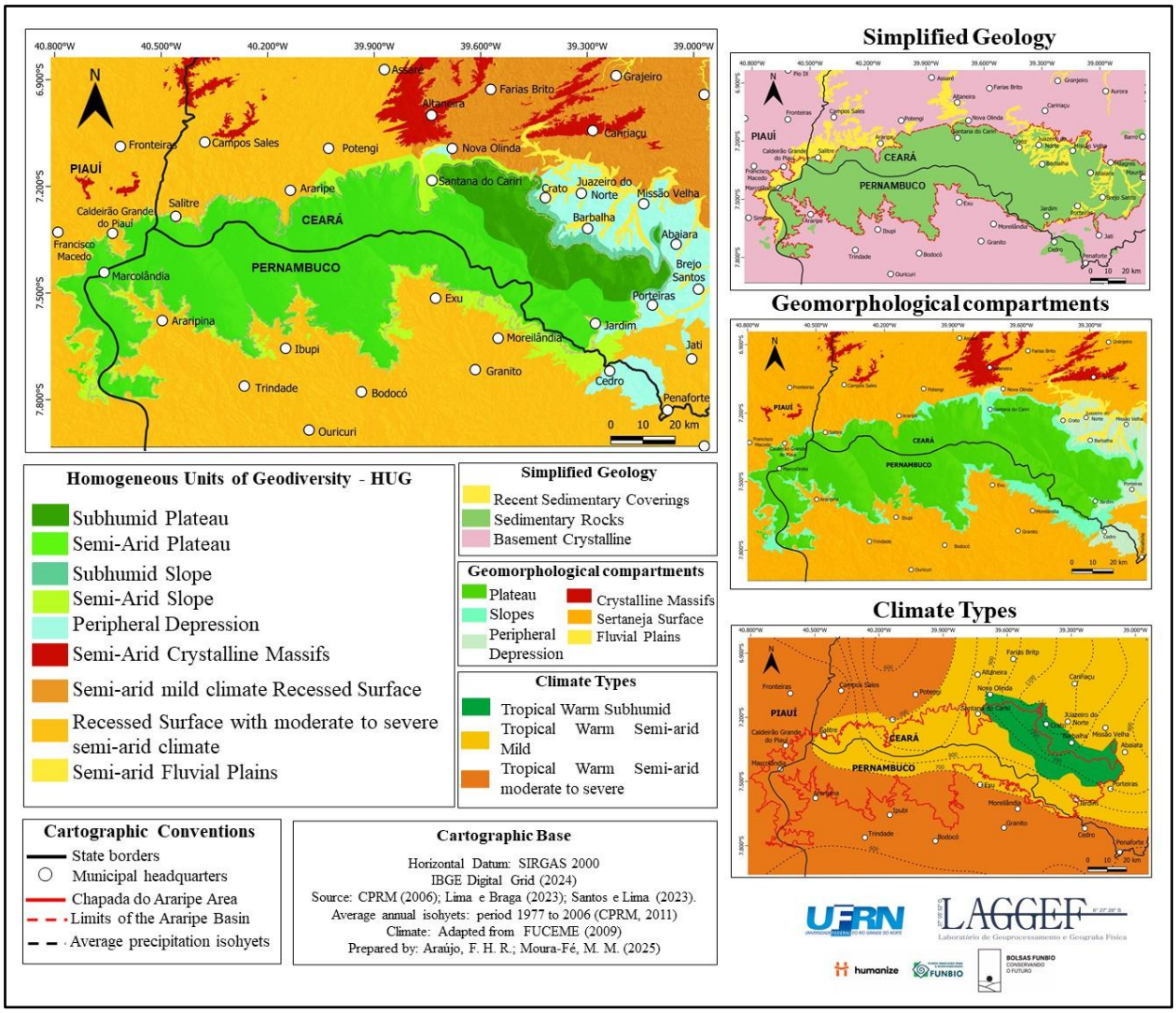
Source: Adapted from Burkhard [45] ; Araújo, Souza and Diniz [16] .

3. RESULTS

3.1 Homogeneous Geodiversity Units – HGU

Upon analysing the abiotic elements that make up the geodiversity of the Chapada do Araripe and adjacent areas, 9 HGUs were delineated: sub-humid plateau; semi-arid plateau; sub-humid slope; semi-arid slope; peripheral depression; semi-arid crystalline massifs; low-lying area with a mild semi-arid climate; low-lying area with a moderate to severe semi-arid climate; semi-arid river plain. Figure 5 shows the spatial distribution of these units within the study area.

Fig. 5: Homogeneous Units of Geodiversity (HGU) in the Chapada do Araripe and adjacent areas.



Source: Araújo; Moura-Fé (2025).

The HGUs 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 HGUs in Chapada do Araripe and adjacent areas.

HGU	LITOLOGY	GEOMORPHOLOGY	SOILS	CLIMATE	Vegetation shaped by geodiversity	AN EXCEPTIONAL LANDSCAPE?
Sub-humid Plateau	Sedimentary – Exu Formation	Sedimentary Plateau	Clay soils and Latosols	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 Latosols	Mild Semi-arid Tropical	Common Caatingas of the semi-arid region	NO
Sub-humid Slope	Sedimentary – Santana Formation	Slope	Lithic Neosols, Argisols, Latosols	Sub-humid Tropical	Evergreen forest influenced by the interaction of climate, relief and soil	YES
Semi-arid slope	Sedimentary – Santana Formation	Slope	Litholic Neosols, Argisols, Latosols	Mild Semi-arid Tropical	Common Caatingas of the semi-arid region	NO
Peripheral depression	Sedimentary – Barbalha, Abaiara, Missão Velha, Brejo Santos and Mauriti formations	Peripheral Depression	Latossols, Vertissols,	Sub-humid Tropical and Mild Semi-arid Tropical	Common Caatingas of the semi-arid region	NO
Depressed Area of Mild Semi-arid Climate	Crystalline – granites and gneisses	Sertaneja surface	Luvisols and Neosols	Mild Semi-arid Tropical	Common Caatingas of the semi-arid region	NO
Depressed surface with moderate to severe semi-arid climate	Crystalline – granites and gneisses	Sertaneja surface	Luvisols and Neosols	Mild semi-arid tropical	Common Caatingas of the semi-arid region	NO
Semi-arid crystalline massifs	Crystalline – granites and gneisses	Crystalline Massifs and Inselbergs	Neosols – Lithols and Regolits	Tropical Semi-arid	Common Caatingas of the semi-arid region	NO
Semi-arid River Plain	Alluvial deposits	Plain	Fluvial Neosols	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 Latossolos 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 HGU 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 Argisols, Latosols and Lithic Neosols 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 Depression: 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 Latossols developed on the rocks of the Missão Velha Formation and Vertissols in the flat or gently undulating areas of this unit[26]. Annual rainfall reaches 1100 mm, characterising a sub-humid climate.

Depressed Areas with a 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. Neosols, which are thin in depth, are the most common in these HGUs. Climatic characteristics are responsible for dividing this area into two homogeneous units of geodiversity: the Low-lying Surface with a mild semi-arid climate and the Low-lying 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 Fluvial 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 in the Chapada do Araripe and surrounding areas

The geodiversity of the study area provides benefits to society by supporting different types of abiotic ecosystem services, which have been identified and are distributed across the HGUs, and may occur directly or indirectly, as shown in Table 5.

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

	CATEGORIES / BENEFITS	HOMOGENEOUS GEODIVERSITY UNITS - HGU								
		Sub-humid Plateau	**Semi-arid Plateau**	**Sub-humid Slope**	**Semi-arid Slope**	**Peripheral Depression**	**Depression with a mild semi-arid climate**	**Depressed Area with Moderate to Severe Semi-arid Climate**	**Semi-arid crystalline massifs**	**Semi-arid river plains**
REGULATION	1.1 Climate and Air Quality Regulation	Direct	Indirect	Direct	None	Absent	Absent	Absent	Indirect	Absent
	1.2 Atmospheric and/or Oceanic Regulation	Direct	Indirect	Direct	Absent	Absent	Absent	Absent	Absent	Absent
	1.3 Water Regulation	Direct	Indirect	Direct	Indirect	Indirect	Absent	Absent	Absent	Direct
	1.4. Water Quality/Water Purification and Waste Treatment	Direct	Direct	Direct	Absent	None	Absent	Absent	Absent	Direct
	1.5 Flood control	Direct	Direct	Direct	Indirect	Absent	Absent	Absent	Absent	Direct
	1.6 Natural Risk and Erosion Control	Direct	Direct	Direct	Indirect	Absent	Absent	Absent	Absent	Direct
	TOTAL	6	6	6	3	1	0	0	1	4
		Sub-humid Plateau	**Semi-arid Plateau**	**Sub-humid Slope**	**Semi-arid Slope**	**Peripheral Depression**	**Depression with a mild semi-arid climate**	**Depressed Area with Moderate to Severe Semi-arid Climate**	**Semi-arid crystalline massifs**	**Semi-arid Fluvial Plains**
SUPPLY	2.1 Freshwater supply	Indirect	Direct	Direct	Indirect	Direct	Direct	Direct	Absent	Direct
	2.2 Industrial materials	Direct	Absent	Absent	Direct	Direct	Forward	Straight	Absent	Absent
	2.3 Energy (renewable and non-renewable)	Not applicable	Direct	Direct	Not available	Direct	Straight	Home	Absent	Absent
	2.4 Nutrients and minerals for healthy growth	Direct	Indirect	Direct	Indirect	Direct	Direct	Direct	Direct	Direct
	2.5 Ornamental features	Absent	Absent	Direct	Direct	Direct	Absent	Absent	Home	Absent

	2.6 Construction materials	Direct	Direct	Direct	Direct	Direct	Straight	Straight	Straight	Straight
	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 Depression**	**Depression with a mild semi-arid climate**	**Depressed Area with Moderate to Severe Semi-arid Climate**	**Semi-arid crystalline massifs**	**Semi-arid river plains**
CULTURAL AND KNOWLEDGE	3.1 Cultural diversity	Absent	Indirect	Direct	Indirect	Direct	Direct	Direct	Direct	Indirect
	3.2 Spiritual and religious values and cultural meanings	Direct	Direct	Direct	Direct	Direct	Straight	Straight	Home	Absent
	3.3 Knowledge systems	Direct	Direct	Direct	Direct	Direct	Indirect	Indirect	Direct	Indirect
	3.4. Education	Direct	Direct	Direct	Direct	Direct	Straight	Straight	Straight	Straight
	3.5 Artistic inspiration	Direct	Direct	Direct	Direct	Direct	Straight	Straight	Home	Absent
	3.6 Aesthetics	Indirect	Indirect	Direct	Direct	Direct	Direct	Indirect	Direct	Indirect
	3.7 Social relations	Indirect	Indirect	Direct	Direct	Direct	Direct	Direct	Indirect	Indirect
	3.8 Sense of place	Direct	Direct	Direct	Direct	Straight	Straight	Straight	Straight	Absence
	3.9 Cultural Heritage and Geoheritage	Direct	Direct	Direct	Direct	Direct	Straight	Straight	Home	Absent
	3.10 Health and well-being	Direct	Direct	Direct	Direct	Absent	Absent	Absent	Absent	Indirect
	3.11 Nature-based recreation and tourism	Direct	Direct	Direct	None	Direct	Indirect	Indirect	Direct	Indirect
	TOTAL	10	11	11	10	10	10	10	10	7
	CATEGORIES / BENEFITS	**Sub-humid Plateau**	**Semi-arid Plateau**	**Sub-humid Slopes**	**Semi-arid Slopes**	**Peripheral Depression**	**Depression with a mild semi-arid climate**	**Depressed Area with Moderate to Severe Semi-arid Climate**	**Semi-arid crystalline massifs**	**Semi-arid river plains**
SUPPO	4.1 Soil formation processes	Direct	Direct	Direct	Direct	Direct	Straight	Straight	Straight	Direct
	4.2 Burial and storage	Not applicable	Direct	Not applicable	Absent	Direct	Straight	Forward	Absent	Absent
	4.3 Platform for human activity	Direct	Direct	Direct	Absent	Direct	Home	Forward	Direct	Indirect

RT	4.4 Biogeochemical cycling	Direct	Direct	Direct	Straight	Straight	Straight	Straight	Straight	Direct
	4.5 Habitat Provision	Direct	Direct	Direct	Direct	Direct	Straight	Straight	Straight	Straight
	TOTAL	4	5	4	3	5	5	5	4	4

The ecosystem services provided by geodiversity vary according to the HGU. 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 geodiversity ecosystem services.

ES Categories	Geodiversity Homogeneous Units (HGU)	Score assigned	Degree of relevance	Relevance capacity
Regulatory Services	Sub-humid Slope	6.00	5	Very high
	Semi-arid Plateau	5.25	5	Very high
	Sub-humid Plateau	6.00	5	Very high
	Peripheral Depression	0.75	0	Not relevant
	Semi-arid hillside	2.25	2	Low
	Low-lying area with a mild semi-arid climate	0	0	Not applicable
	Depressed area with moderate to severe semi-arid climate	0	0	Not applicable
	Crystalline Massifs Semi-arid	0.75	0	Not applicable
	Semi-arid river plains	4.00	5	High
	Sub-humid Slopes	5.00	5	Very High

Provisioning services	Semi-arid Plateau	3.75	3	Medium
	Sub-humid Plateau	3.75	3	Average
	Peripheral Depression	6.00	5	Very high
	Semi-arid hillside	4.50	4	High
	Low-lying area with a mild semi-arid climate	5.00	5	Very high
	Depressed area with moderate to severe semi-arid climate	5.00	5	Very high
	Crystalline Massifs Semi-arid	3.00	3	Medium
	Semi-arid river plains	3.00	3	Media
Cultural and Knowledge Services	Sub-humid Slope	11.00	5	Very high
	Semi-arid Plateau	10.25	5	Very high
	Sub-humid Plateau	9.50	5	Very high
	Peripheral Depression	10.0	5	Very high
	Semi-arid hillside	9.75	5	Very high
	Low-lying area with a mild semi-arid climate	9.50	5	Very high

	Depressed area with moderate to severe semi-arid climate	9.25	5	Very high
	Crystalline Massifs Semi-arid	9.75	5	Very high
	Semi-arid river plains	5.50	3	Medium
Support Services	Sub-humid Slopes	4.00	4	High
	Semi-arid Plateau	5.00	5	Very high
	Sub-humid Plateau	4.00	4	High
	Peripheral Depression	5.00	5	Very high
	Semi-arid hillside	3.00	3	Medium
	Low-lying area with a mild semi-arid climate	5.00	5	Very high
	Depressed area with moderate to severe semi-arid climate	5.00	5	Very high
	Crystalline Massifs Semi-arid	4.00	4	High
	Semi-arid river plains	3.75	4	High

In turn, Table 7 presents the overall valuation of all ecosystem services provided by geodiversity in the study area.

Table 7. Overall valuation of the relevance of geodiversity ecosystem services.

	Geodiversity Homogeneous Units – HGU	Score assigned	Degree of relevance	Relevance capacity	Ranking
Geodiversity ES	Sub-humid Slope	26.00	5	Very high	1
	Semi-arid Plateau	24.25	4	High	2
	Sub-humid Plateau	23.25	4	High	3
	Peripheral Depression	21.75	4	High	4
	Semi-arid hillside	19.50	3	Medium	5
	Depressed Basin in a Mild Semi-arid Climate	19.50	3	Average	5
	Depressed Area with Moderate to Severe Semi-arid Climate	19.25	3	Average	7
	Crystalline Massifs, Semi-arid	17.50	3	Average	8
	Semi-arid river plains	16.25	3	Average	9

4. DISCUSSION

The common characteristics among the elements of geodiversity, particularly geology, geomorphology and climate, form the HGUs in the Chapada do Araripe and its adjacent areas. Abiotic 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 and the sub-humid slope exhibit distinctive natural features, particularly regarding soil, relief and climate, setting them apart from the other units identified and analysed. For this reason, they are considered exceptional landscapes.

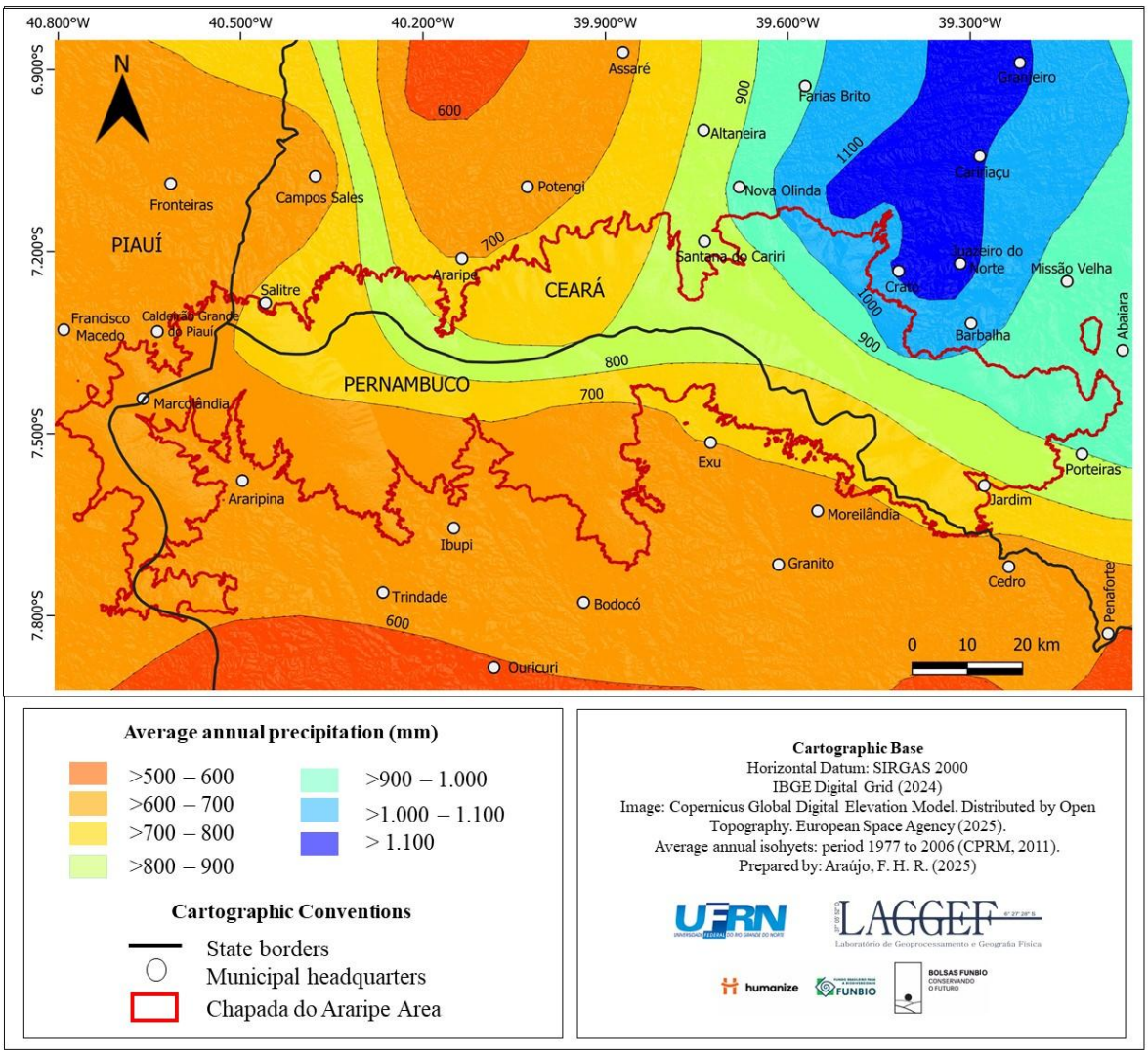
Exceptional landscapes provide more geodiversity ecosystem services than the surrounding landscapes, which is most evident in the provision of regulatory services. The sub-humid slope is the HGU that provides the most services, being the only one classified as having very high relevance in the general classification. The sub-humid slope and the sub-humid plateau, however, are the only HGUs 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.

As highlighted by Araujo, Diniz and Souza[16], 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 6). 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 7). 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 three exceptional landscapes were delineated by the presence of more humid vegetation in the case of the sub-humid HGUs, particularly the tropical forest found in the Araripe National Forest (Figure 8) 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 8).

Fig. 6: Average annual precipitation in Chapada do Araripe and adjacent areas.



Source: Araújo (2025).

Fig. 7: Climate and air quality regulation and atmospheric regulation in the Chapada do Araripe.

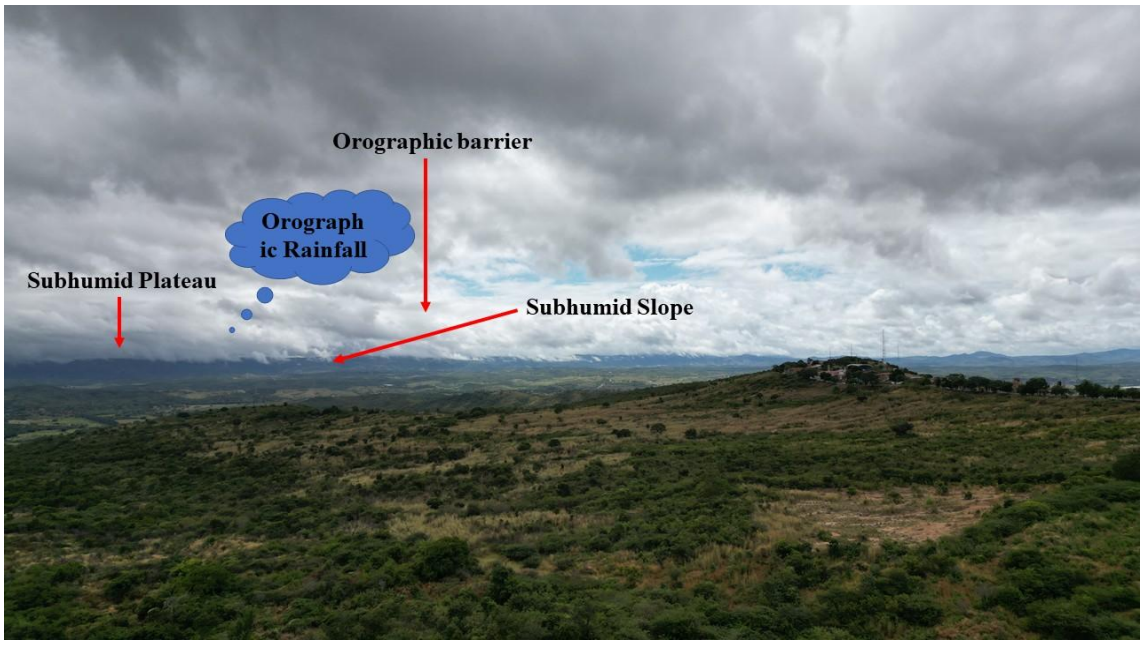
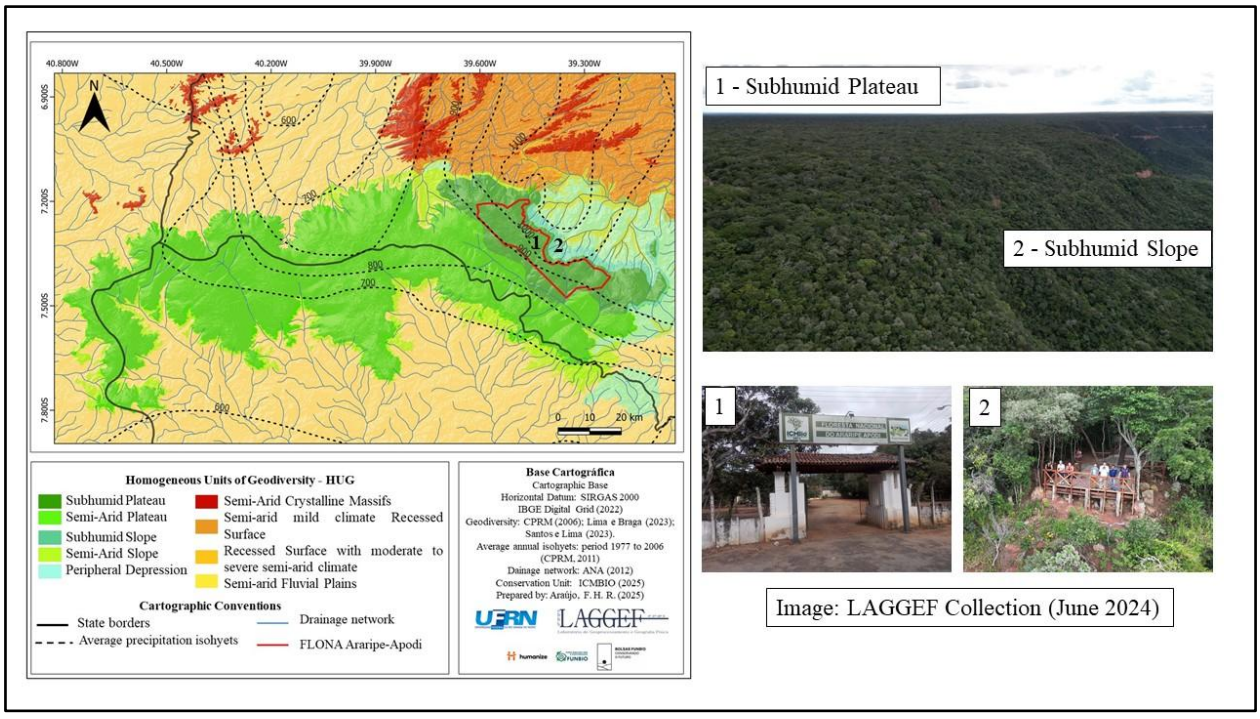


Fig. 8: Delimitation of the subhumid exception units and the Araripe National Forest.



Source: LAGGEF Collection (2024); Araújo (2025).

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 Depression showed a low degree of relevance in the provision of regulation services. Only the indirect 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 Depression area. This HGU 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 SE. These same characteristics are found in the semi-arid crystalline massifs, which differ only in terms of altitude, a factor that determines the provision of the benefit described in section 1.1. The altitude of the massifs provides good ventilation conditions, which have a direct influence on climate regulation and air quality.

Situated near the orographic barrier of the Chapada do Araripe, the semi-arid river plains demonstrated a high capacity for ES provision. 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

As for provisioning services, the sub-humid slope, the Peripheral Depression and the low-lying areas stand out, having obtained maximum scores in the assessment of relevance. Next comes the semi-arid slope, with a high degree of relevance. Only four benefits were identified in the sub-humid part comprising the plateau, which classifies it as having medium relevance. The semi-arid plateau, the semi-arid massifs and the semi-arid river plains also showed 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 Depression, forming the river plains and reaching the lower-lying 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 low-lying area 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 particular 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 9).

Fig. 9: Extraction of Pedra Cariri limestone , on the semi-arid slope, Nova Olinda-CE.

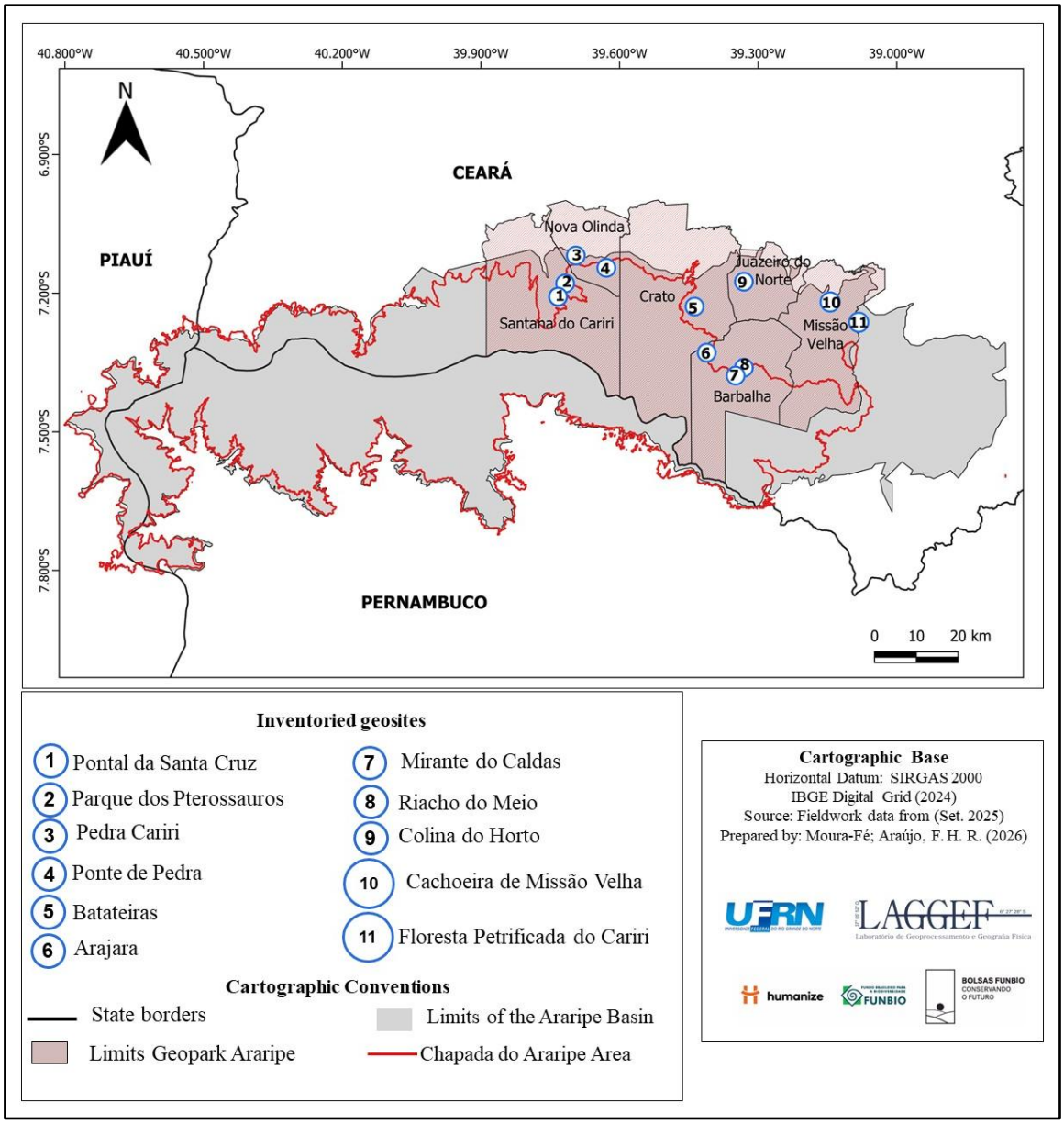


The energy supply, item 2.3, is most evident on the semi-arid plateau, which has wind turbines generating power. Also noteworthy is the production of solar energy via photovoltaic panels on the lower-lying areas, which benefit from the topography ranging from gentle to undulating and the hot climate 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, highlighting the region's cultural richness. Of note are the semi-arid plateau and the sub-humid slope, which possess all the benefits and achieved a very high degree of relevance. The sub-humid plateau, the semi-arid slope, the peripheral depression, the low-lying area with a mild semi-arid climate, the low-lying area with a moderate to strong semi-arid climate, and the semi-arid crystalline massifs also achieved the maximum score in the assessment of relevance. The semi-arid river plains showed moderate relevance in 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 10). 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. 10: 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 particular 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 clearly evident. 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 11). 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 aforementioned benefits.

Fig. 11 - View of Arajara Park, Arajara District.



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 Depression, 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, whose natural characteristics are most clearly evident. Special mention should be made of the low-lying 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 12). 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. 12: The physical characteristics of the Exu Backlands served as artistic inspiration for Luiz Gonzaga, whose legacy has been preserved in the eponymous municipality.



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 13), 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. 13: Statue of Padre Cícero at the Colina do Horto geosite.

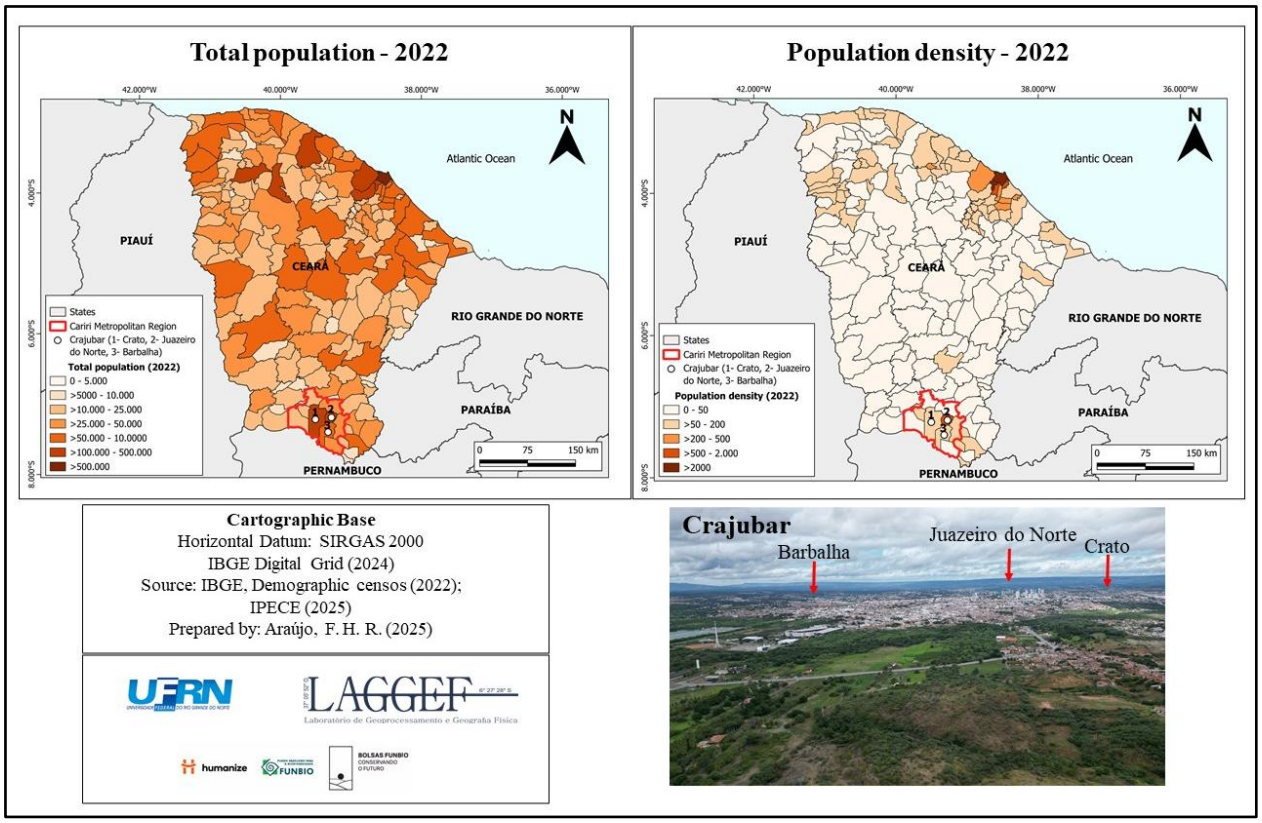


Seven cultural benefits were identified in the semi-arid river plains, the vast majority of which are provided indirectly. The presence of water facilitates, in some cases, social interactions and succinctly highlights the aesthetic value during the rainy season, which is not necessarily

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 semi-arid plateau, the Peripheral Depression, the low-lying area with a mild semi-arid climate, the low-lying area with a moderate to severe semi-arid climate, and the semi-arid river plains are of great importance in terms of the provision of support services. All the benefits were found in these units. Of particular note is the presence of towns located in these units, highlighting the provision of items 4.2 and 4.3, relating to burial, storage and a platform for human activities. On the flat terrain of the semi-arid plateau lies the town of Marcolândia (Piauí state), the only municipality whose administrative centre is situated on the summit of the plateau. The gently undulating terrain provides these benefits across both low-lying areas. These characteristics, combined with the higher humidity resulting from the Araripe mountain range, lead to greater population density in the study area. It lies within the Peripheral Depression, 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 14), the largest urban agglomeration in the Brazilian semi-arid region, with around 600,000 inhabitants, alongside the regions of Petrolina (Pernambuco state) and Juazeiro (Bahia state), on the banks of the São Francisco River. There are more than 500,000 inhabitants in the three conurbated cities alone, with particular emphasis on Juazeiro do Norte, which, according to IBGE estimates for the population in 2025, has already exceeded 300,000 inhabitants[48].

Fig. 14: Population data for the state of Ceará, with a focus on the Crajubar region.

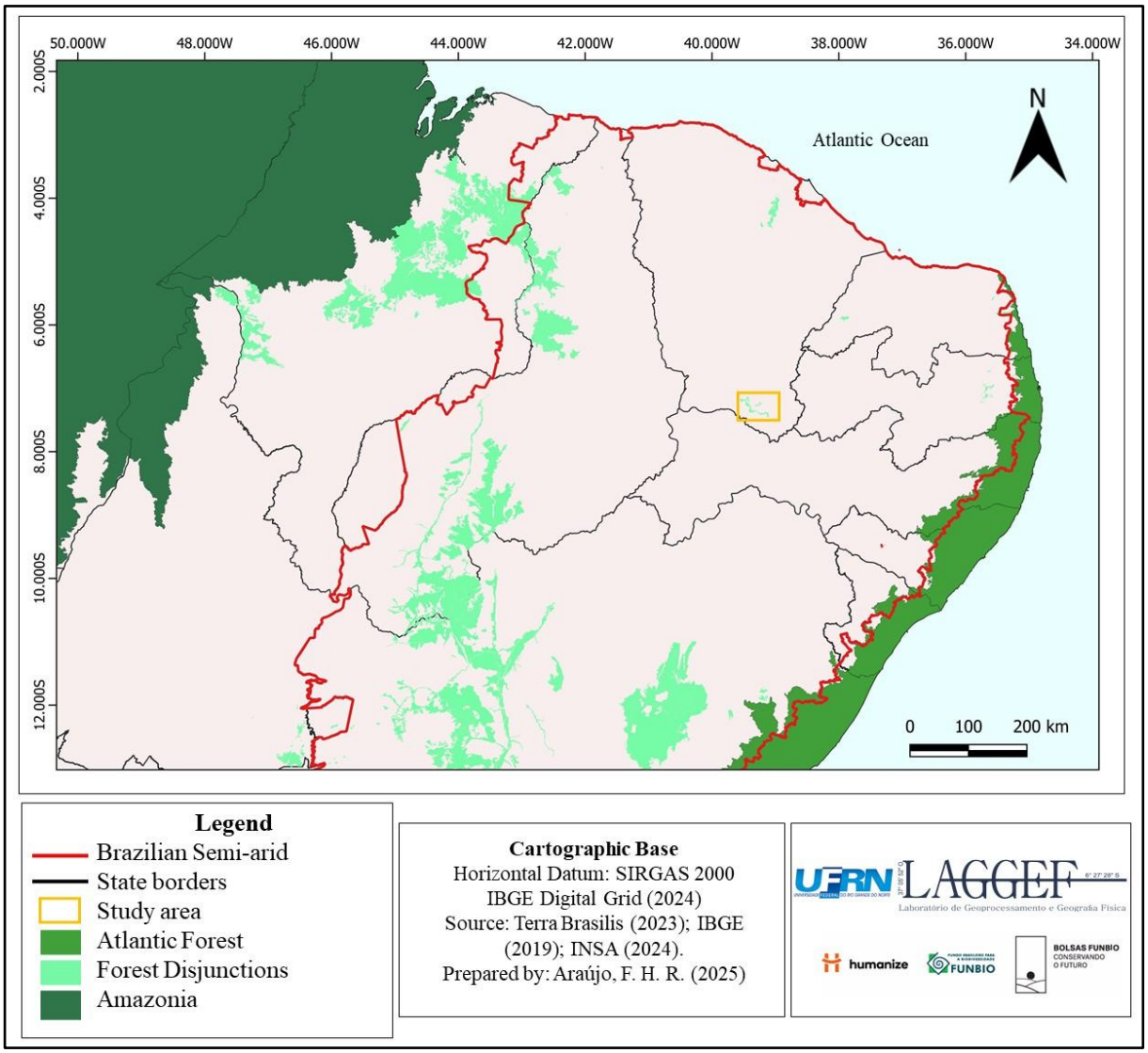


Source: Araújo (2025).

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 15). 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 abiotic ecosystem services, which are essential for sustaining, regulating and maintaining these forest disjunctions.

Fig. 15: Atlantic humid forest disjunctions in Chapada do Araripe.



Source: Araújo (2025).

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 16). 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 millions 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 A Arajara, Cocos and Gameleiras streams, located on the subhumid slope of the Araripe, covered by patches of humid forest.

Fig. 16: The species *Kingsleya attenboroughi* Pinheiro & Santana, 2016 (freshwater crab) inhabiting the perennial springs of the subhumid slope of the Chapada do Araripe.



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.

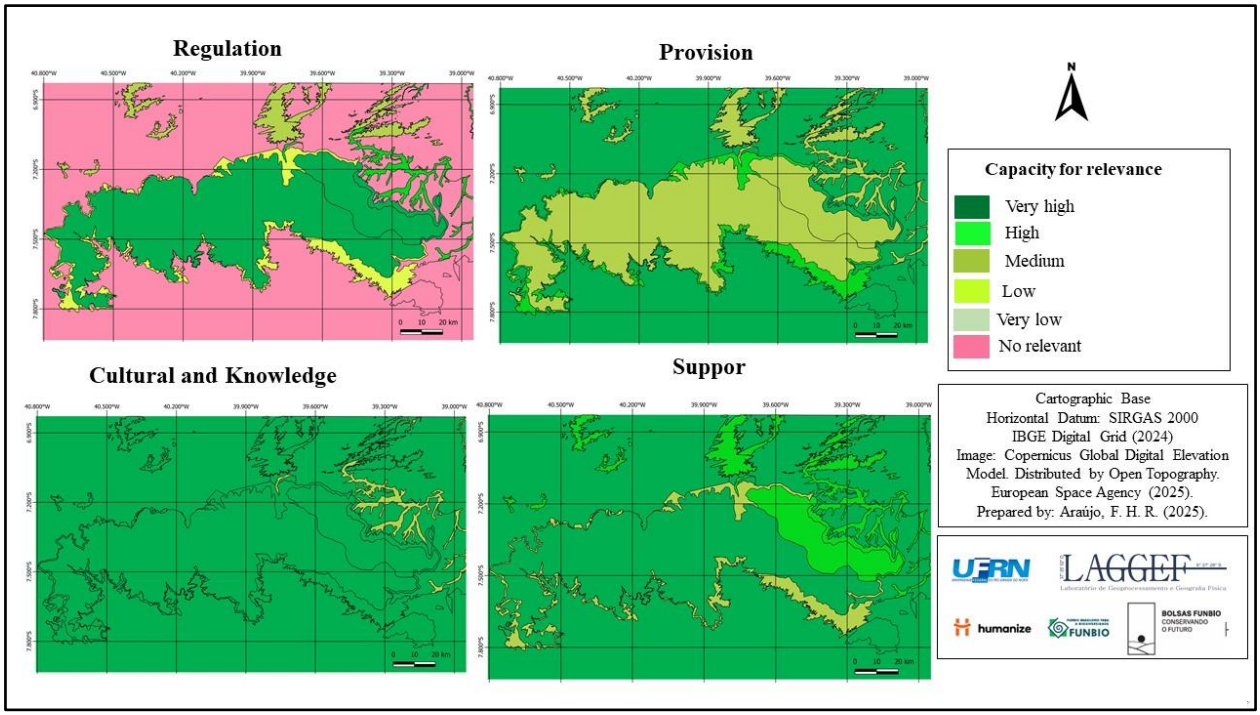
The semi-arid slope received an average rating for relevance, whilst the sub-humid slope is highly relevant. The terrain, consisting mainly of escarpments, hinders the provision of benefits 4.2 and 4.3. The latter, however, is recorded on the sub-humid slope, as part of the city of Crato (CE) is situated 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 particular 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 neosols was observed, with the presence of vegetation and even agriculture.

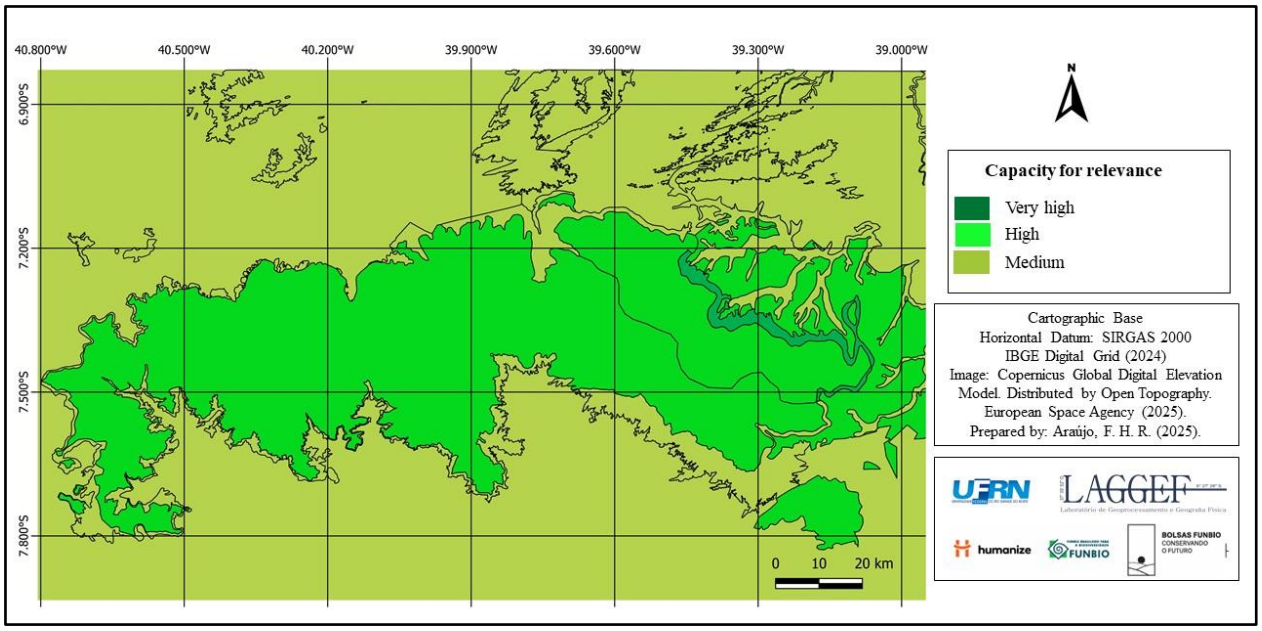
In view of the above, it is evident that geodiversity plays an essential role in the provision of ES in the study area. To better understand the assessment of the degree of relevance, Figure 17 presents the capacity for relevance of each category of ES in the HGUs. Figure 18, meanwhile, presents the overall assessment of the capacity for relevance of the HGUs in the study area.

Fig. 17: Capacity for relevance of each category of geodiversity ecosystem services in the HGU.



Source: Araújo (2025).

Fig. 18: Overall assessment of relevance in the HGU.



Source: Araújo (2025).

After assessing the capacity for relevance of geodiversity ecosystem services (ES) in the HGUs 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 HGU 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 Araripe antbird (*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

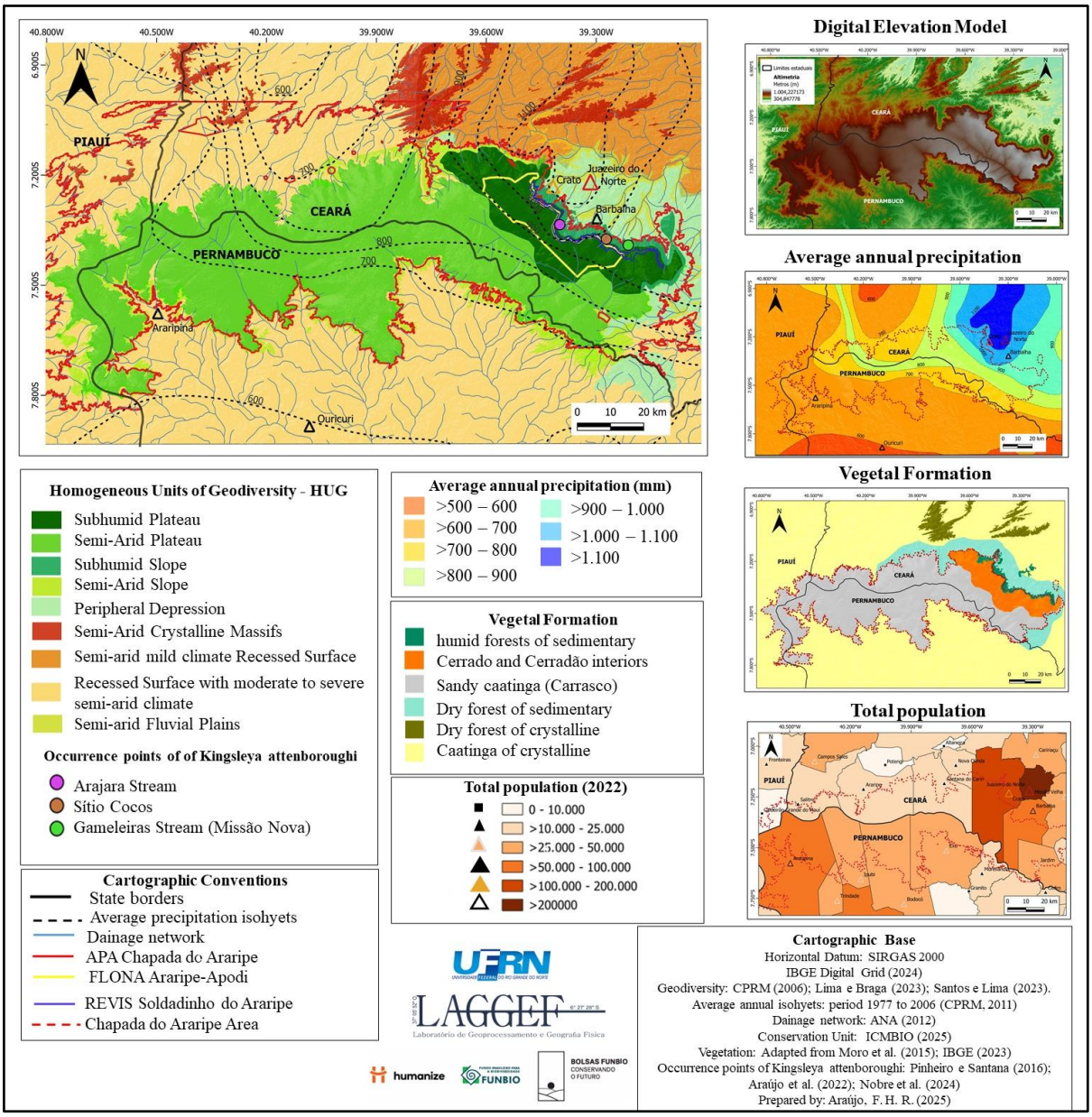
protected area of great importance for the conservation of the Soldadinho do Araripe and *Kingsleya attenboroughi*, both of which depend entirely on the preservation of the springs for their survival. There is also the Chapada do Araripe Environmental Protection Area (APA), which covers the entire plateau. 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.

The Cariri region of Ceará is a population density sustained exclusively by the unique interaction between lithology, soil, relief, climate and hydrography, which has enabled the development of an extremely prosperous society in the midst of Brazil's poorest region – a true oasis in the Brazilian semi-arid zone.

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 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 HGU, 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. Our method identified this area as being of the highest importance. The rivers that supply the largest urban agglomeration in the Brazilian semi-arid region have their source within this HGU.

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 HGUs, 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 HGUs, 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 ES 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 HGU 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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