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MARINE HARDBOTTOM ENVIRONMENTS IN THE BEACHES OF CEARÁ STATE, EQUATORIAL COAST OF BRAZIL

Ambientes marinhos rochosos nas praias do estado do Ceará, costa equatorial do Brasil

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ABSTRACT

This paper is a literature review on marine hardbottom environments (MHE) that emerge in coastal regions in the Brazilian state of Ceará. This stretch of the Brazilian coast houses several rock formations, which are widely distributed in the intertidal zone. These formations have various origins and composition, ranging from crystalline rocks to biogenic structures, but most are composed by sandstones. These substrates support biodiverse ecosystems that produce valuable environmental goods and services, which have historical and socioeconomic relevance for the state. Despite their importance, they are currently threatened by various types of local and global stressors, and a consistent government effort to protect them is still lacking. There are many knowledge gaps regarding these formations and new studies are needed to support conservation actions involving these ecosystems.

Keywords: reef, beachrock, sandstone, intertidal zone, benthos.

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RESUMO

Este artigo é uma revisão da literatura sobre ambientes marinhos rochosos que surgem em regiões costeiras do estado brasileiro do Ceará. Esse trecho da costa brasileira abriga diversas formações rochosas, que estão amplamente distribuídas na zona entremarés. Essas formações possuem origens e composições diversas, que vão desde rochas cristalinas até estruturas biogênicas, mas a maioria é composta por arenitos. Esses substratos sustentam ecossistemas biodiversos que produzem bens e serviços ambientais valiosos, que têm relevância histórica e socioeconômica para o estado. Apesar de sua importância, eles estão atualmente ameaçados por vários tipos de estressores locais e globais e ainda falta um esforço consistente do governo para protegê-los. Existem muitas lacunas de conhecimento a respeito dessas formações e novos estudos são necessários para subsidiar ações de conservação envolvendo tais ecossistemas.

Palavras-chave: *recife,* beachrock*, arenito, zona entremarés, bentos.*

INTRODUCTION

The structure and function of benthic marine ecosystems are influenced by their substrates (Gerlach, 1972). The predominant composition of the seabed, which may be either clay, sand, gravel, or rock, influences the species that inhabit an environment and ultimately the biological communities established in and on the substrate (Little, 2000). Rocky bottom environments provide stable bases that give a two-dimensional character to marine ecosystems (Little, 2000; Wahl, 2009). This allows for the development of rich epibenthic communities, which are very productive and serve as a basis for aquatic food webs (Wahl, 2009).

Three main types of marine hardbottom environments (MHE) are usually recognized in the coastal zone of Brazil (<30m deep): (1) the rocky shores, consisting of resistant rocky platforms along the shoreline, mainly of crystalline nature, capable of withstanding the erosive processes of the coast (Naylor; Stephenson & Trenhaile, 2010); (2) biological reefs, which originate from the growth of calcium carbonate precipitating organisms, such as corals, calcareous algae and bryozoans (Bastos *et al*., 2018); and (3) sandstone reefs, or rocky reefs, that arise from the accumulation and cementation of sediments in a beach and shoreface environment (Araújo *et al*., 2020; Bittencourt *et al*., 2008; Branner, 1904).

In Brazil, the rocky shores are more abundant in the Southeastern and Southern regions, where the proximity of the Serra do Mar mountain range causes the crystalline bedrock to emerge on the coast (Coutinho *et al*., 2016). Biological reefs are more common near the coasts of the Northeastern region because of the climatic and oceanographic conditions that favor the proliferation of reef-building organisms (Leão *et al*., 2016).

The so-called sandstone reefs appear along the entire tropical coast of the Southwest Atlantic Ocean, interrupting strips of sand beaches from the coast of Espírito Santo state (Brazil) to Central America. In Brazil, these extensive inorganic platforms co-occur with biological reefs and can act as a substrate for the proliferation of reef-building organisms (Bittencourt *et al*., 2008; Branner, 1904). Contrary to typical rocky shores, which generally emerge from outcrops of the crystalline basement, sandstone reefs usually appear in a sedimentary context with little lithification and more recent in geological history (Barros, 2005; Branner, 1904; Silva *et al.*, 2019). In addition, it is common for sandstone reefs to only occur near the water surface, in foreshore and shoreface regions, and even when they emerge from erosive processes, the diagenesis of these rocks may often be associated with the influence of seawater (Branner, 1904; Freire, 2017; Morais, 1969; Waring, 1914). Therefore, such formations are usually considered distinct from typical rocky shores (Coutinho *et al.*, 2016).

Despite the wide distribution of different types of marine hardbottom environments, few studies have focused on the MHE on the Brazilian equatorial coast (approximately between latitudes 4ºN and 5ºS). The shore zone in this area mainly contains sandstone reefs and is far from the largest biogenic formations of the country, located on the coast of Bahia state and in the Abrolhos Archipelago (around 18ºS) (Castro & Pires, 2001; Laborel-Deguen *et al.*, 2019). Although the northern rocky environments have been mentioned in the literature since the colonial period (Branner, 1904; Hawkshaw, 1875; Spix & Martius, 1828), little is known about their geology, ecology, and socio-environmental roles. Furthermore, most of the existing information is dispersed and in the form of gray literature, which makes it difficult to understand the importance of these equatorial ecosystems.

In order to narrow this information gap, this review seeks to compile and analyze the existing data on the MHE that occur on the shore of Ceará state, which is located in the eastern sector of the equatorial coast of Brazil. Therefore, we present an overview of the current knowledge about these ecosystems, indicating investigation pathways that can be explored in future studies.

Brief history of the studies on MHE of Ceará

The occurrence of MHE in Ceará has been recorded since the colonial period. Rock formations have been depicted in the coastal zone of the state on 17th century maps (Albernaz, 1640). However, the historical importance of these formations is still little recognized. For example, the construction of the port of Fortaleza (capital city of the state) played a significant role in the history of Ceará. But until the 19th century, in the absence of more adequate natural harbors, ships used to dock in the shallow coves formed by headlands (the Mucuripe headland in the case of Fortaleza), using rocky outcrops as anchorage (Giraldes, 1898). Particularly the so-called "Porto reef", which was located nearshore of present-day Fortaleza's downtown, functioned as a de facto harbor in the city for decades (Hawkshaw, 1875). Such rocky reef already figures prominently in the "Planta da Costa do Ciará Grande da ponta do Mucuripe the Jacarecanga" elaborated in 1745 by Luis Xavier Bernardes (Jucá Neto, 2007).

Because of this relationship between the MHE and the Fortaleza City port, the first studies on marine rocky bottom formations in Ceará were within the scope of naval engineering. Some of the first detailed descriptions of MHE on the Ceará coast are contained in the engineering report and maps by Francisco Giraldes, dated 1810 (Castro, 1997; Giraldes, 1898). The author describes the Mucuripe cove in Fortaleza as divided by three formations, namely the reef of Velha (farthest from the coast), the Occidental reef (today known as the Grande reef) and the Meridional reef (the Porto reef). In his report, Giraldes proposed civil works in the latter formation to improve its capacity to house vessels (Giraldes, 1898). The author also depicts some beach outcrops in his maps (Castro, 1997).

This mapping of rocky reefs has been expanded upon by other authors. The "Planta do Porto e Villa de Fortaleza", made by Silva Paulet in 1813, portrays two other MHE in the Mucuripe cove, the Meireles stone (to the east) and the Arpoadouros (near the Ceará river mouth, to the west). Paulet's map also indicates the existence of at least six formations contiguous to the beach, between the tip of the Mucuripe headland and the Porto reef (Costa, 2014). Besides the Fortaleza City port, Silva Paulet also elaborated the "Planta do Porto e Villa do Aracati" in 1813, which depicts a rocky outcrop near the mouth of the Jaguaribe river, next to the Maceió headland, on the east coast of Ceará (Barbosa, 2004). Posterior urban and engineering projects also portrayed prominently the MHE in Fortaleza, particularly the Porto reef (Matos & Vasconcelos, 2010; Matos, 2011).

Perhaps the first study to bring a geological characterization of the MHE in Ceará was the report on the Brazilian ports by Hawkshaw (1875). The author listed the rocky formations in the Mucuripe cove (which he named as the reefs of Meireles, Estrella, Velha and Grande), indicated an arenitic constitution for these MHE, and estimated a thickness of about 1 m for the Porto reef. In addition, he mentions a depth reduction in the berth formed by the Porto reef due sediment accumulation and depicts a less prominent rocky outcrop than in previous reports. This suggests the occurrence of environmental changes in the area during the 19th century.

Biological descriptions made of the MHE in Ceará during the 19th century were brief despite the arrival of several naturalists to the region. Spix and Martius (1828) mischaracterized the Ceará coast as having "coral banks" similar to the "coral reefs" found further south on the Brazilian coast, in the states of Rio Grande do Norte, Paraíba and Pernambuco. Nevertheless, these authors recorded the occurrence of four genera of bivalve mollusks and one genus of calcareous algae (that they considered to be corals) in these formations, which makes Spix and Martius (1828) one of the first biological descriptions of the MHE of Ceará.

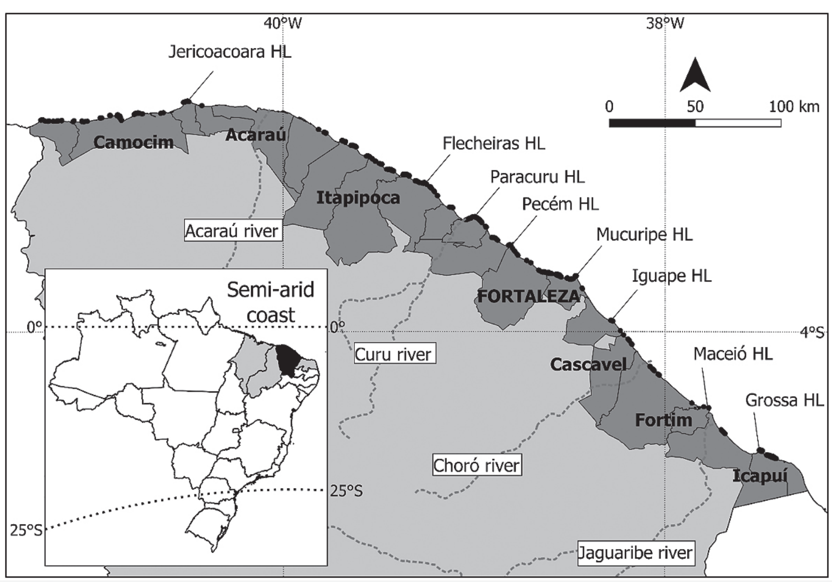
Broader scientific investigations on the Ceará MHE occurred starting in the 20th century. Branner (1904) extensively researched the rocky reefs of Brazil and reported that he saw the "reef of Ceará". However, this author did not carry original research on these MHE and simply reproduced notes made by Hawkshaw (1875). Therefore, the first comprehensive scientific work regarding MHE in Ceará was carried out by Waring (1914). This author investigated rocky reefs located on the equatorial coast of Brazil, including the cities in Ceará of Icapuí, Fortim, Fortaleza and Camocim. Waring (1914) records for the first time the occurrence of two types of rock in the MHE of Ceará: sandstones cemented by calcium carbonate and sandstones cemented by iron oxide. This author also reported that the occurrence of live coral formations is restricted to the easternmost sector of the Brazilian equatorial coast (in Rio Grande do Norte state), but that dead coral platforms may exist further west. Lastly, he brings the first unequivocal account of anthropogenic impacts on these MHE, reporting that the area of the Porto reef had been occupied by a breakwater, and no evidence of a natural substrate could be observed in the year of 1913. In fact, the total or partial removal of the Porto reef had been considered in previous projects (Hawkshaw, 1875). And the construction of the breakwater at the beginning of the 20th century caused a serious silting problem (Morais, 1980), ultimately burying what was left of the rocky substrate.

Throughout the twentieth and twenty-first centuries, studies on the MHE of Ceará continued within the scope of port engineering. During that period, the state experienced intense urbanization and industrialization (Fachine, 2007; Paula, 2015), which required studies and monitoring of coastal environments (Freitas; Vieira & Araújo, 2009; Magini; Martins & Pitombeira, 2014; Morais, 1972; Ximenes Neto; Morais & Pinheiro, 2018b). However, from the second half of the twentieth century, studies began to be conducted by universities, and became more comprehensive. Besides advancing the biological (e.g., Ferreira & Pinheiro, 1966; Matthews-Cascon & Lotufo, 2006) and geological (e.g., Morais, 1969; Barros, 2005) characterization of these environments, it was given more attention to their ecological dynamics (e.g., Rabelo; Soares & Matthews-Cascon, 2013; Rabelo *et al.*, 2015) and their susceptibility to anthropogenic impacts (e.g., Soares & Rabelo, 2014; Portugal *et al.*, 2016). Therefore, it is now possible to devise a clearer picture of the environmental and economic roles of the MHE on the coast of Ceará. The remainder of the present review is mostly based on these latter studies.

Distribution of MHE in beaches of Ceará

Marine hardbottom environments occur along most of the coastal zone of Ceará (Figure 1). Although some authors suggested a sparse occurrence of MHE (Smith & Morais, 1984), the maps published in Ceará (2016) and Morais *et al.* (2018) show that these formations are widely distributed throughout the state. For example, Pinheiro, Morais and Maia (2016) observed the occurrence of rocky outcrops in 82 of 216 beaches analyzed (38% of the total). However, a more complete measure of the quantity and the area occupied by these formations is still lacking.

Figure 1 – Distribution of marine hardbottom environments on beaches of Ceará state, Brazil (black dots). Coastal municipalities are shown in dark gray. Solid lines indicate major headlands (HL). Dashed lines represent main rivers. States comprising the semi-arid coast in the Brazilian equatorial margin are shown in the detail



Many of the MHE on Ceará beaches appear as fringes or cemented terraces that remain in contact with the continent. This is different from the formations on the east coast of Brazil, where extensive lines of sandstone are observed in shoreface regions, bordering the coastline (Araújo *et al.*, 2020; Branner, 1904). In addition, some of the MHE in Ceará are subject to high hydrodynamics and burial / exhumation cycles (Barros, 2005). These factors control the ecological dynamics of these environments and cause periodic variations in the space occupied by these formations, a phenomenon whose magnitude remains unknown (Barros, 2005).

Origin and geomorphological context of MHE in Ceará beaches

The coast of Ceará state extends for 573 km within the Semi-Arid equatorial coast of Brazil (Diniz & Oliveira, 2016). The state has a hot semi-arid climate, with rainfall restricted to the first half of the year. Due to the dry climate, the region lacks major rivers or other main sources of organic matter and nutrients for the coastal zone. Oceanographic conditions are subject to semidiurnal mesotides and are under the influence of the trade winds and the North Brazil Current, which result in westward flowing coastal current and longshore drift (Morais *et al.*, 2018).

Current coastal landscapes, including the MHE, are the result of depositional and erosive processes along the geological history (Claudino-Sales, 2016). The coastal zone and the continental shelf of Ceará are within the sedimentary basins of Ceará and Potiguar. These basins originated from the separation of the South American and African continents during the end of the Cretaceous period (Claudino-Sales, 2016). Stratigraphically, these basins can be divided into three supersequences, namely rift, post-rift and drift. The rift and post-rift supersequences are dated to the Lower Cretaceous and are characterized by continental (Pendência and Mundaú Formations) and transitional / coastal environments (Paracuru and Alagamar Formations), respectively. The drift supersequence has occurred between the Albian and the Recent and is mostly characterized by shallow- to deep-water marine environments (e.g. Ubarana, Guamaré, Tibau and Jandaíra Formations) (Condé et al., 2007; Pessoa Neto et al., 2007). Also, in this last supersequence, it is worth noting the deposition of the Barreiras Group, which occurred between 23-17 Ma ago (Miocene) in continental environments (Lima, 2008). Currently, sediments from the Barreiras Group stand out covering a large proportion of Brazil’s tropical coast (Lima, 2008), including the Ceará state, where it typically appears as sandy clay cliffs (Silva *et al.*, 2019). Most of the other sediment deposits that appear in the coastal zone of Ceará – such as dunes, plains, marine terraces, and recent river deposits – are of Quaternary origin (Morais *et al.*, 2018). In addition to these sedimentary deposits, there are some pre-Cambrian crystalline outcrops on the Ceará coast (Claudino-Sales, 2016).

After their deposition, these sedimentary deposits (and the crystalline outcrops) have been reworked by weathering and erosive processes. Past sea level changes likely had a marked influence on the current geomorphology of the coastal zone of Ceará (Claudino-Sales, 2016). There is evidence of a marine transgression during the last interglacial period (130-115 ka ago), when the ocean reached 8 m above the current level (Irion; Morais & Bungenstock, 2012; Meireles *et al.*, 2005). This transgression was followed by an intense marine regression during the last ice age (115-14.5 ka ago), which left the entire continental shelf of Ceará exposed to the air (Meireles *et al.*, 2005). After the last ice age, during the Holocene, the sea level rose again. Along most of the Brazilian coast, it surpassed the current mark about 7,000 years ago and reached a maximum elevation of about 5 m around 5,100 years ago (Angulo; Lessa & Souza, 2006). Since then it has been receding towards the current level (Angulo; Lessa & Souza, 2006).

This same pattern of fluctuations during the Holocene was proposed by some researchers for the Ceará coast (Barros, 2005; Meireles *et al.*, 2005). However, these studies were mostly based on the sea level fluctuation curves produced for the east coast of Brazil (Angulo; Lessa & Souza, 2006). Specific analyses of the semiarid coast produced conflicting results. Some authors suggested multiple occurrences of a higher sea level associated with high frequency variations in the past 7,000 years (Bezerra; Barreto & Suguio, 2003). Subsequent studies have not been able to confirm such high frequency fluctuations, sustaining the more traditional pattern of a higher sea level followed by a continuous drop towards the current mark, with eventual low amplitude variations (Barros, 2005; Caldas *et al.*, 2006). Remarkably, and contrary to these studies, some authors have questioned the evidence of a higher sea level during the Holocene between Ceará and the north coast of Brazil (Morais *et al.*, 2009; Irion; Morais & Bungenstock, 2012; Vital, 2014). According to these authors, this region should be currently experiencing a transgressive (i.e., rising sea level), not a regressive (i.e., falling sea level), phase (Irion; Morais & Bungenstock, 2012). Other studies, while supporting the occurrence of a higher Holocene sea level on the Ceará coast, indicated that the fluctuations were mainly caused by local changes in circulation pattern, thus being distinct from those observed on the east coast of Brazil (Vasconcelos, 2014). Finally, later research went full circle, again describing for the state a regressive pattern consistent with the rest of the Brazilian coast (Ximenes Neto, 2020). Due to these large discrepancies among studies, further investigations are needed to resolve the sea level history along the semiarid coast of Brazil.

Despite these doubts regarding the timing and magnitude of past sea level fluctuations, the influence of depositional and erosive processes throughout the Quaternary on the coast of Ceará is undisputed (Morais *et al.*, 2018). Currently, about 30% of the state's shoreline is undergoing erosion and another 17% show an erosive tendency (Morais *et al.*, 2018). Such processes resulted in an intense supply and transport of sediments along the littoral zone, despite the absence of large rivers. The resulting landscape is a low coastal relief dominated by extensive sandy beaches, often bordered by cliffs and / or large dune fields formed by the inland deposition of coastal sediment (Claudino-Sales, 2016; Morais *et al.*, 2018). Numerous rocky outcrops, of diverse composition and origin, interrupt these sandy beaches originating the MHE of the state (Figure 2).

In other Brazilian states, similar rocky outcrops may support bioconstructions and many of the Brazilian coral reefs have developed on such bases (Bittencourt *et al.*, 2008). However, in Ceará, corals and calcareous algae do not usually dominate these substrates. This lack of large carbonate frameworks may be due to the harsh meteo-oceanographic conditions in the state, such as the high temperatures and intense sediment dynamics, a factor that is known to negatively affect the formation of Brazilian coral reefs (Bittencourt *et al.*, 2008). While the east coast of Brazil, home to the largest coral formations of the country (Leão *et al.*, 2016), is dominated by waves, the semiarid coast shows a stronger interaction between waves, tides and winds, along with a drier climate (Vital, 2014). Together, these factors result in a highly energetic environment (Rodríguez *et al.*, 2016; Vital, 2014), with a complex pattern of sediment deposition (Claudino-Sales; Wang & Carvalho, 2018), which may have hindered the development of a carbonate facies on the coastal MHE of Ceará.

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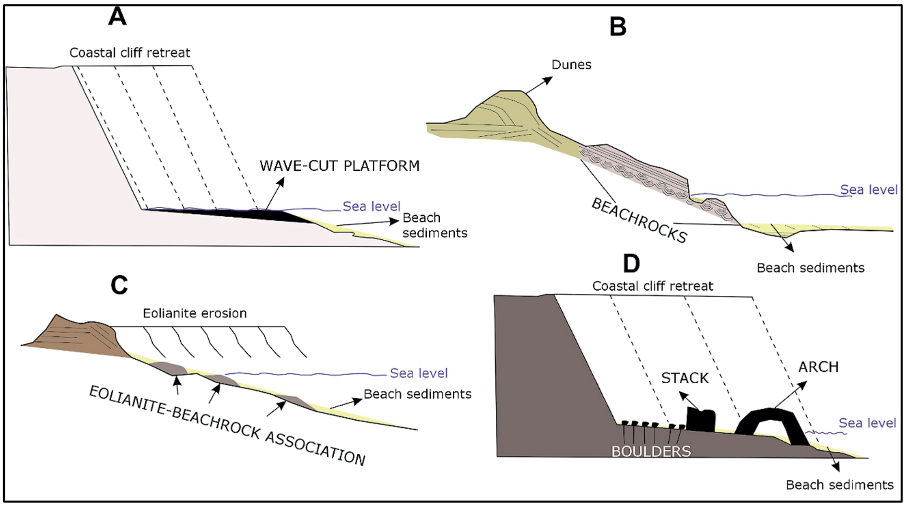
Figure 2 – Geological-geomorphological patterns of occurrence of marine hardbottom environments on beaches in Ceará, Brazil. (A) wave-cut platform (associated with rigid and friable substrates); (B) typical beachrocks; (C) eolianite-beachrock association; and (D) erosive features associated exclusively with rigid substrates (e.g., stacks, arches, and boulders)



Historical and geomorphic factors may also have contributed to this low occurrence of biogenic reefs. Most of the coastal Brazilian coral reefs developed during the last marine transgression (7,000-5,000 years ago) (Leão *et al.*, 2016). Since then, these formations have faced erosion due to the decreasing sea level (Leão *et al.*, 2016). But, as previously mentioned, the sea level history and the morphology of the inner continental shelf may be distinct along the Ceará coast (Morais *et al.*, 2009; Irion; Morais & Bungenstock, 2012; Vital, 2014; Vasconcelos, 2014; Morais *et al.*, 2019). Therefore, erosive processes may have been acting more intensely or for a longer period in the state, thus limiting the proliferation of reef building organisms. In fact, some authors have reported the occurrence of relict calcareous bioconstructions in some stretches of the Ceará coast, usually on other types of rocky substrate (Claudino-Sales & Carvalho, 2014; Meireles *et al.*, 2005). As the climate in the state has been relatively hot and dry during most of the Holocene (Meireles *et al.*, 2005) it is unlikely that these ancient reefs were built under milder climatic conditions. Therefore, these biogenic formations may reflect the importance of historical factors in explaining the current lack of biogenic formations on the Ceará coast. Nevertheless, these biogenic reefs have been poorly studied so far, and we still have little information on their age, composition, and depositional environment.

Geology of MHE in the beaches of Ceará

The MHE of Ceará are composed of sedimentary and metamorphic rocks. Sedimentary rocks include biogenic rocks (Cretaceous limestones and Quaternary bioconstructions) and clastic rocks. Clastic rocks are mostly sandstones (or conglomerates) cemented by calcium carbonate, iron oxide or silica. The main metamorphic rocks in the MHE of Ceará are quartzites and gneisses (Figure 3).

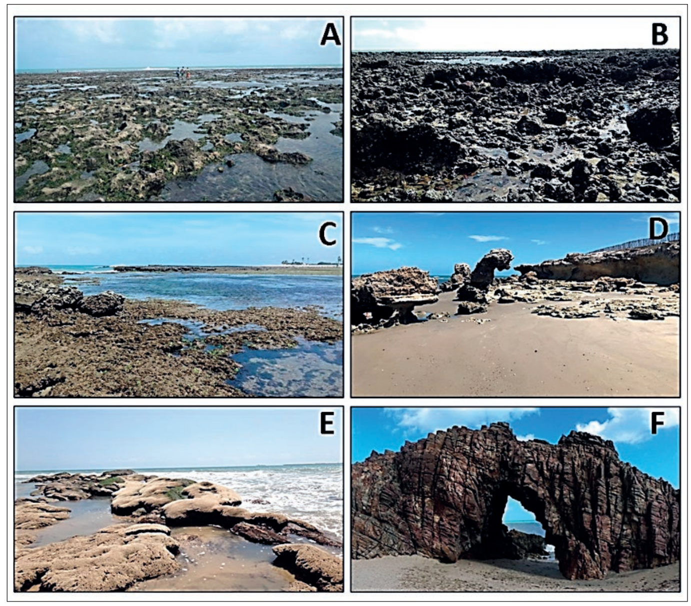


Figure 3 – Marine hardbottom environments in the state of Ceará, Brazil. (A) sandstones cemented by calcium carbonate (beachrock) at Dois Coqueiros beach, Caucaia; (B) sandstones cemented by iron oxide at Farol beach, Camocim; (C) ferruginous sandstone containing bioconstructions (according to Carvalho, 2003) at Pedra Rachada beach, Paracuru; (D) sandstone cemented by silica with erosive features in the Maceió headland, Fortim; (E) outcrops of crystalline rock covered by constructions of *Phragmatopoma* sp. at the Pecém headland, São Gonçalo do Amarante; and (F) crystalline outcrop at the Jericoacoara headland

Sandstones cemented by calcium carbonate (beachrocks)

Sandstones cemented by calcium carbonate, also called beackrocks, originate from the cementation of quartz grains (mainly sands and gravels) by the precipitation of $CaCO_3$ in a beach or shoreface environment (Danjo & Kawasaki, 2014). These rocks usually present a grayish color, flat relief slightly inclined towards the sea, and a disposition parallel to the coastline (Barros, 2005; Morais, 1969).

Beachrocks are distributed throughout the entire coast of Ceará. However, studies of petrological and stratigraphic characterization of these formations are rare (Barros, 2005; Mesquita *et al.*, 2016; Morais, 1969; Vasconcelos, 2014). Very general classifications are common, which include all MHE that are not associated with cliffs automatically in the beachrock category (Ceará, 2016). This practice can lead to rock misidentifications and errors in determining their geological evolution.

In general, these rocks appear to have formed recently, with their cementation occurring during the Quaternary and especially in the Holocene. For example, the age of the sandstones at Sabiaguaba beach (Fortaleza, CE – Brazil) was estimated at 2,700 ± 140 years (Claudino-Sales, 2002). Beachrocks located at the mouth of the Curu River near the municipality of Paraipaba (west of Fortaleza) were estimated at 3,360 ± 80 years (Carvalho, 2003). And outcrops located between the municipalities of Itapipoca and Acaraú (west of Paraipaba) were aged between 3,110 and 1,490 years (Vasconcelos, 2014). All these studies used the C^{14} method for dating these rocks and the origin of these formations have been attributed to a higher past sea level (Carvalho, 2003).

Higher sea levels may also have formed beachrocks in the municipalities of Cascavel (Pinheiro, 2003) and Beberibe (Barros, 2005), both located east of Fortaleza. This possibility is based on the position of these rocks just above the high tide line. However, no dating was conducted to confirm the age of these latter formations. Additionally, it is necessary to consider this hypothesis of origin in light of the uncertainties about the sea level history along the coast of Ceará (Irion; Morais & Bungenstock, 2012; Morais *et al.*, 2009). For example, research suggests that the appearance of rocks above the waterline may be due to the action of the waves (Morais *et al.*, 2009) or vertical tectonic pulses (Barros, 2005). In any case, the age of beachrocks dated in Ceará thus far is similar to that of the most recent group of beachrocks found on the equatorial coast of Brazil (Vieira, 2005), and older formations may also occur in the state (Barros, 2005).

Regarding the origin of these rocks, two main processes have been suggested for the diagenesis of beachrocks on the Ceará coast (Barros, 2005). The first process is the precipitation of aragonite or high-magnesium calcite directly from the sea water, which may occur in a shallow marine environment. The second process is the precipitation of low-magnesium calcite from the dissolution of bioclastic sediments, which results from the mixture between salt water and fresh water. Both processes can alternate, predominating in different stages of the formation of these rocks (Barros, 2005). Furthermore, even when beachrocks are formed in a shallow marine environment, the presence of a river may influence the flow of sediments along the coast, providing material for the construction of these rocks (Barros, 2005).

Besides these two main processes, it has also been suggested that some of these beachrocks were formed from the cementation of barrier islands, not necessarily under the influence of a river (Barros, 2005; Claudino-Sales, 2002). Furthermore, studies on the west coast of Ceará highlight the association between beachrocks and eolianites. Both rock types are similarly comprised of quartz grains cemented by calcium carbonate, but while the former originates under marine influence (Mesquita *et al.*, 2016), the cementation of the latter occurs in continental environments (Carvalho *et al.*, 2009). Even so, the erosion of eolianites located near the coast may favor the recementing of carbonate blocks on beaches, contributing to beachrock formation (Freire, 2017). Therefore, many different processes, acting under distinct environmental conditions, may have influenced the formation of beachrocks on the coast of Ceará (Barros, 2005).

Sandstones cemented by iron oxide

Ferruginous sandstones and conglomerates are arguably the most abundant rock in Ceará MHE (Claudino-Sales; Wang & Carvalho, 2018; Waring, 1914). Unlike beachrocks, which are formed by beach sands cemented by calcium carbonate, ferruginous sandstones are formed by sediments from the Barreiras Group (a continental terrigenous sediment deposit that occurs along most of the Brazilian coastline) and quaternary fluvial deposits (Ximenes Neto, 2020), cemented by iron oxide (Morais, 1969). These rocks emerge in the intertidal zone due to coastal erosion and are the main components of the wave-cut platforms at the base of cliffs in the state. They usually have a reddish color, a very rugged relief, and are never parallel to the coast (Morais, 1969). Ferruginous sandstones may form a continuous pavement or appear as boulder accumulations in the intertidal zone.

Like beachrocks, very general criteria are often used to identify ferruginous sandstones, most rocks associated with cliffs being classified as such (Ceará, 2016). This classification disregards the possible occurrence of other rock types in the wave-cut platforms and the possibility that the ferruginous sandstones may also emerge in beach and shoreface environments. In addition, specific data on the diagenesis of ferruginous sandstones are lacking. Some of these rocks are superficially similar to the crusts formed by the laterization of sediments from the Barreiras Group (Morais, 1969), which formed at different times and under distinct paleoenvironmental conditions along the Ceará coast

(Julio *et al.*, 2013; Souza, 2017). However, chemical analyses point to some differences in composition between ferruginous sandstones and true laterites (Morais, 1969). In particular, the concentration of iron and the hardness are generally higher in the former (Morais, 1969; Waring, 1914). Some authors have proposed that this iron enrichment is due to the contact between the Barreiras sediments and seawater, which suggests that at least the final stage of the diagenesis of these rocks occurred in recent times and under some marine influence (Waring, 1914). The influence of the sea in the formation of ferruginous sandstones is clear in cases that such rocks have calcium carbonate as a secondary cement (Morais, 1969), or when they exhibit some type of biological encrustation (Waring, 1914). However, further studies are needed to characterize the origin of the iron-bearing cements and to evaluate how their deposition occurred in the different formations found along coastal Ceará.

Other sandstones

In addition to calcareous (i.e., beachrocks) and ferruginous sandstones, other types of arenite may appear on the coast of Ceará. At the Maceió headland (municipality of Fortim, east coast of Ceará), sandstones cemented by silica emerge on the beach (Branco; Lehuguer & Freire, 2001; Carvalho Neta & Claudino Sales, 2019; Leite, 2016). In the east coast of Ceará, the Barreiras Group encounters other sediment deposits. One of these sedimentary layers, the Tibau formation, emerge in the Maceió headland, giving rise to outcrops mainly composed of silicified sandy-clayey sediments (Carvalho Neta & Claudino Sales, 2019). These formations were deposited from the end of the Cretaceous to the Recent (Pessoa Neto *et al.*, 2007) having been reworked throughout the Quaternary, what resulted in the formation of live cliffs and wave-cut platforms in the intertidal zone across the headland (Carvalho Neta & Claudino Sales, 2019).

At the mouth of the Coreaú River, near the municipality of Camocim (west coast of Ceará), conglomerates cemented by a ferruginous-siliceous lateritic material are observed at the foot of cliffs (Marques; Claudino-Sales & Pinheiro, 2019a). These rocks are associated with the Camocim Formation, a sedimentary deposit of Neogene age that is probably associated with the Barreiras Group (Marques; Claudino-Sales & Pinheiro, 2019b), but which is still little recognized in geological studies (Marques; Claudino-Sales & Pinheiro, 2019a). Due to their high consolidation, several erosive forms appear in these formations, such as wave-cut platforms, stumps, stacks, and caves (Ximenes Neto *et al.*, 2018a).

Biogenic rocks

The occurrence and structure of biogenic reefs remain poorly studied on the coast of Ceará. Although some authors point to the existence of coral reefs in the far east of the state (Leão *et al.*, 2016), this classification lacks the support of detailed biological and geological characterizations. However, ancient bioclastic limestones appear at the base of cliffs in the Ponta Grossa headland (municipality of Icapuí). These limestones belong to the Jandaíra Formation, dating from the Cretaceous, and their formation may be associated to shallow marine ecosystems, of low energy and biodiversity (Sousa *et al.*, 2009).

On the west coast of Ceará, some authors describe the occurrence of ancient biological incrustations formed by mollusks (oysters and vermetids) or corals bordering several headlands in the region, such as the promontories of Paracuru, Flecheiras, and Jericoacoara

(Carvalho, 2003; Claudino-Sales; Wang & Carvalho, 2018; Claudino-Sales & Carvalho, 2014; Meireles *et al*., 2005). Such reefs may have developed on ancient wave-cut platforms, beachrock lines, or even directly on the crystalline basement (Claudino-Sales & Carvalho, 2014). To date, only one study has dated these formations, using C^{14} to estimate an age of 1,560 ± 60 years for vermetid samples from the Pecém beach (municipality of São Gonçalo do Amarante) (Carvalho, 2003). Therefore, we still lack data on the age, species composition or environmental setting of these bioconstructions, and further studies are urgently needed to characterize them from both biological and geological perspectives.

Besides the calcareous reefs, other bioconstructions occur on the coast of Ceará. For example, polychaetes of the genus *Phragmatopoma* build structures formed by agglutinated beach sand (Freitas *et al*., 2019). Such formations occupy a relevant area, usually covering other rock types. However, only recently they have been subjected to scientific analyses (Freitas *et al*., 2019) and there are still no assessments of their role in the coastal zone of the state.

Metamorphic rocks

Outcrops of crystalline rock, formed predominantly by quartzites and gneisses, appear discontinuously along the coast of Ceará, notably in the promontories of Mucuripe, Iguape, Pecém and Jericoacoara (Claudino-Sales & Carvalho, 2014). Most authors agree that such rocks are among the oldest on the Ceará coast, with pre-Cambrian age (but see Smith & Morais, 1984). Their emergence on the coast is associated with recent erosive processes, but it also constitutes evidence of the rupture of the Gondwana and the separation of South America and Africa (Claudino-Sales, 2016). These consolidated substrates appear as a wide variety of forms, such as stacks, arches, isolated blocks, wave-cut platforms, and caves.

Mixed environments

Many of the MHE in Ceará have more than one type of rock. Wave-cut platforms may be covered by beachrocks (Irion; Morais & Bungenstock, 2012); biological structures can appear on crystalline and sedimentary rocks (Meireles *et al*., 2005); and beachrocks and crystalline rocks can present ferrous layers that mask their true nature (Julio *et al*., 2013; Morais, 1969). This mixture reflects the geological history of these formations and needs to be analyzed on a case-by-case basis. This diversity of rocks hinders the construction of general maps of the different types of MHE in the state and causes inconsistencies in the classification of certain rock formations (Ceará, 2016; Claudino-Sales & Carvalho, 2014). Therefore, further characterization efforts are needed to better describe these rock types and their geological history.

BIOLOGICAL ASPECTS

Biodiversity in the MHE of Ceará

Benthic communities of coastal MHE are dominated by macroalgae (Carneiro, 2017; Matthews-Cascon & Lotufo, 2006). This vegetation plays an important structuring role by constituting habitats that can be occupied by other organisms, increasing the biodiversity and productivity of these ecosystems (Barros & Rocha-Barreira, 2013; Cavalcante *et al*., 2014; Diniz, 2008; Veras, 2011). In these environments, the coverage of calcium carbonate-producing species (i.e., corals and calcareous algae) is likely relevant, but usually secondary (Soares; Rabelo & Matthews-Cascon, 2011). In other biogeographic regions, such as the Caribbean and the Indo-Pacific Ocean, a similar pattern is often considered as a sign of environmental degradation. However, in Brazil, the dominance of macroalgae is usually the norm in coastal rocky environments (Aued *et al.*, 2018; Carneiro & Oliveira, 2018; Cruz-Motta *et al.*, 2020; Freitas & Lotufo, 2014). This peculiarity may be attributed to a general tendency of lowering sea levels over the past millennia, which exposed Brazilian formations to high degrees of erosion and sedimentation (Leão *et al.*, 2016).

The coastal current that flows consistently from east to west without significant barriers (Bittencourt *et al.*, 2005) provides an intense connectivity between the formations of Ceará and those from eastward states, mainly Rio Grande do Norte and Paraíba (Barroso; Lotufo & Matthews-Cascon, 2016; Freitas & Lotufo, 2014; Horta *et al.*, 2001; Moura, 2003). Accordingly, the species inhabiting MHE in Ceará are usually found elsewhere on the Brazilian tropical coast. However, there are some possible endemisms in the state, such as the sea slug *Tritonia khaleesi*, the ascidian *Styela cearense*, and the macroalgae *Halymenia cearensis*. New studies that focus on such organisms can help to reposition the MHE of Ceará in the biogeographic context of Brazilian reef environments.

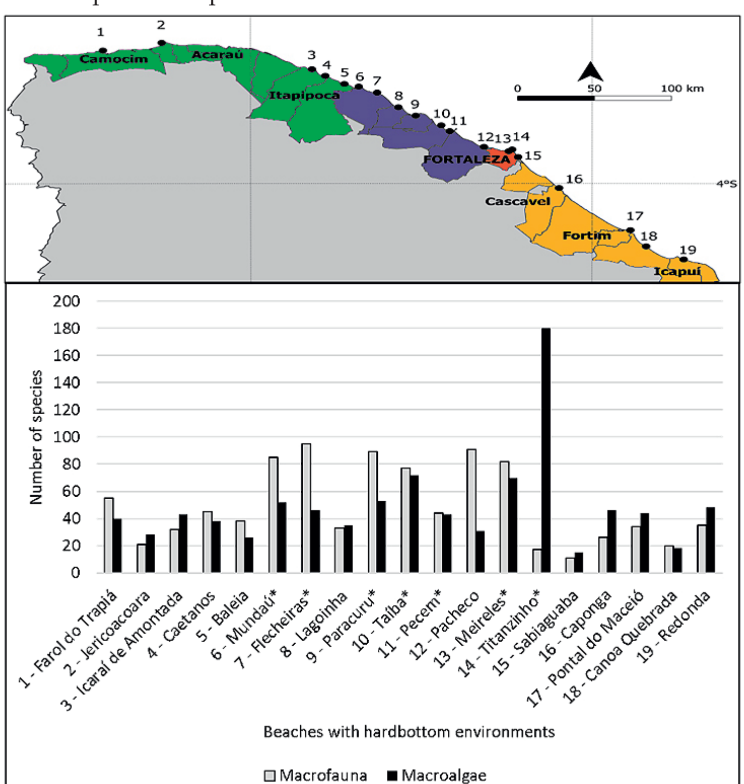
Despite these biogeographical similarities, environmental conditions on the coast of Ceará tend to be quite energetic, with high insolation, temperature, hydrodynamics, and sedimentation during most of the year (Morais *et al.*, 2018). Some of the MHE even experience cycles of burial and exhumation, which result in considerably inhospitable habitats that sustain communities at different stages of ecological succession (Barros, 2005). These harsh conditions limit the occurrence of some species in the state (Cruz-Motta *et al.*, 2020). In addition, MHE in Ceará often appear connected to the mainland and usually emerge due to erosive processes. These features distinguish them from many of the rocky environments found on the east coast of Brazil (Araújo *et al.*, 2020). This results in differences in the composition of the associated biological communities, mainly in diversity and abundance of rare species (Araújo *et al.*, 2020).

Because of these peculiarities, formations on the Ceará coast have historically been considered as poor in biodiversity (Laborel-Deguen *et al.*, 2019). However, new inventories have been expanding the species record in the state, including hundreds of species of macroalgae (Joventino; Dantas & Maraschin, 1998; Matthews-Cascon & Lotufo, 2006) and dozens of species of fish (Araújo *et al.*, 2000; Cunha *et al.*, 2008; Freitas & Lotufo, 2014; Machado *et al.*, 2015; Marques, 2017), mollusks (Rocha-Barreira *et al.*, 2017), crustaceans (Pachelle *et al.*, 2016), polychaetes, ascidians and cnidarians (Matthews-Cascon & Lotufo, 2006).

Arguably one the most extensive surveys of the biota in these MHE was carried out within the scope of the project of ecological-economic zoning for the coast of Ceará (ZEE) (Cavalcante; Maia & Miranda, 2006). Particularly, the technical reports by Franklin Jr. *et al.* (2005) and Dantas *et al.* (2005), both of which are part of the ZEE, have surveyed tens of MHE in the state, many of which have never been studied before. These technical reports recorded 308 macrofauna and 261 macroalgae species on these formations, with an alpha diversity (i.e. mean number of species per MHE) of 47.2 ± 28.6 and 53.1 ± 34.7, respectively (Figure 4). Contrary to studies that report a low biodiversity in the MHE of Ceará (e.g. Laborel-Deguen *et al.*, 2019), these numbers indicate that there is little noteworthy differences between the richness observed locally in the rocky habitats of the state and that of the more southern rocky formations, particularly regarding the alpha diversity (Araújo *et al*., 2020; Aued *et al*., 2018; Carneiro, 2017; Cruz-Motta *et al*., 2020).

Both Franklin Jr. *et al.* (2005) and Dantas *et al.* (2005) also found large differences among the MHE of Ceará in terms of species composition, most pairs of rocky formations having a Jaccard index smaller than 0.5. This suggests a high spatial variability and high beta diversity in these formations. Accordingly, the MHE of Ceará could be arranged into groups of more or less similar benthic assemblages (Franklin Jr. *et al*., 2005; Dantas *et al*., 2005). These groupings are distributed geographically: the far west group, comprising MHE located between the municipalities of Itapipoca and Camocim; the west group, located between Fortaleza and Itapipoca; the Fortaleza group, including most MHE on the coast of this municipality; and the east group, located between Fortaleza and Icapuí (Figure 4). These groupings appear to be valid for both macrofauna and macroalgae (Franklin Jr. *et al*., 2005; Dantas *et al*., 2005). There are some exceptions though. For example, MHE near the mouth of rivers tend to have a distinct species composition, and for the macroalgae the far west and east groups are remarkably akin to each other, possibly forming a single arrangement of similar composition (Dantas *et al*., 2005).

Figure 4 – Number of species of macroalgae and macrofauna, as recorded by Dantas *et al.* (2005) and Franklin Jr. *et al.* (2005), in coastal marine hardbottom environments (MHE) of Ceará state, Brazil. Asterisks (*) indicate locations where sampling efforts may have varied. Colors in the map represent areas where the MHE share more similar species composition



In addition to expanding taxonomic records, studies along the past few decades also suggested the occurrence of many cryptic species in the coastal MHE of Ceará. Such species generally account for a large proportion of the biodiversity in reef environments (Leray & Knowlton, 2015), but they remain poorly studied in Brazil and especially in Ceará. The inclusion of this cryptic biota in new inventories has the potential to increase the species record for the state, including the discovery of new, undescribed taxa. Furthermore, future investigations must evaluate the diverse microbiota in these MHE. Studies carried out with these microorganisms suggest a potential to explain both biological and chemical phenomena, such as coral bleaching and the chemical diversity observed in these environments (Costa-Lotufo *et al.*, 2018; Jimenez *et al.*, 2013). However, marine microscopic organisms remain little known and explored in the state, and their roles in the MHE are virtually unknown.

Despite these knowledge gaps, it is now clear that the MHE in Ceará are home to a considerable biodiversity, with some rare and possibly endemic species. Therefore, the supposed low richness of these ecosystems seems to be due to a lack of studies and a complex spatial-temporal dynamic of the biological communities in these formations.

Ecological dynamics

Some studies have assessed seasonal variations in species richness, abundance, and composition in coastal MHE of Ceará (Barros & Rocha-Barreira, 2013, 2014; Barros *et al.*, 2013; Matthews-Cascon & Lotufo, 2006). However, despite the climatic variations between the wet and dry seasons, temporal changes are not ubiquitous in the biological communities of these formations, and are sometimes difficult to perceive (Bezerra *et al.*, 2017; Martins; Martins & Matthews-Cascon, 2010; Sousa, 2006). This is probably due to the relatively stable temperature and solar conditions throughout the year, regardless of the changes in rainfall and wind speed. Also, the considerable interannual variations in rainfall may sometimes average out the differences between seasons, diminishing their effects on the biota. On the other hand, some coastal MHE may be subject to seasonally determined sedimentation processes, with alternating erosive and depositional phases (Barros, 2005). These processes may play a relevant role in some cases, as they affect the availability of substrate and increase the risks of burial (Barros & Rocha-Barreira, 2013, 2014). Variations in other time scales, such as decadal cycles, have not yet been described for the Ceará coast and there are no long-term monitoring programs that allow studies on this scale.

Spatial variations are more evident in these ecosystems. There are many microhabitats within a given formation (such as tidal pools, crevices, plateaus, etc.), and even variations in the structure of different MHE along the coast, which affects the distribution and relative abundance of species (Barros & Rocha-Barreira, 2014; Bezerra *et al.*, 2017; Carneiro, 2017; Cunha *et al.*, 2008; Godinho & Lotufo, 2010; Martins; Martins & Matthews-Cascon, 2010; Rabelo *et al.*, 2015; Sousa, 2006; Souza & Matthews-Cascon, 2019; Veras; Martins & Matthews-Cascon, 2013). The degree of air exposure and the distance from the water and the drainage system may be a primary cause of these spatial differences. As such, many species exhibit a clear zonation between the lowest and highest areas of the rocky platforms (Martins; Martins & Matthews-Cascon, 2010; Rabelo *et al.*, 2015; Sousa, 2006; Veras; Martins & Matthews-Cascon, 2013). It is even possible to identify some relatively stable sectors along the vertical gradient, with the supralittoral zone dominated by litorinids, the upper intertidal zone dominated by barnacles and the lower intertidal zone dominated by algae (Matthews-Cascon & Lotufo, 2006). Similarly, the depth of tidal pools influences the fish communities in these environments (Bezerra *et al.*, 2017; Godinho & Lotufo, 2010).

Besides the vertical zonation, there are intense horizontal variations in community structure and composition, which extends parallel to the coastline, not being restricted to a single formation (Barros & Rocha-Barreira, 2014; Bezerra *et al.*, 2017; Carneiro, 2017; Cunha *et al.*, 2008; Godinho & Lotufo, 2010; Souza & Matthews-Cascon, 2019). Therefore, in addition to air exposure, many other factors may affect the spatial heterogeneity and biodiversity of these ecosystems, such as the intensity of marine currents, proximity to river mouths, the degree of wave exposure, the type of substrate, the available area, biological interactions, the distance between formations and anthropogenic impacts (Carneiro, 2017; Godinho & Lotufo, 2010; Portugal *et al.*, 2016).

Most coastal MHE of Ceará have a low relief, with a slight slope towards the sea. In many cases, the rocky substrate may not extend far beyond the lower intertidal zone, with the upper areas remaining entirely covered by sand. This suggests that, at regional scales (from a few kilometers to the entire 573 km of the state's coastline), horizontal variations may be prevalent, being more intense than the vertical changes in species composition (i.e. zonation) (Carneiro, 2017). This could differentiate the MHE of Ceará from temperate rocky shores, which show a vertical zonation pattern that prevails over horizontal changes for hundreds to thousands of kilometers (Chappuis; Terradas & Cefalì, 2014). Further studies are needed to quantify and compare this spatial heterogeneity, since more intense variations along the coast would require more comprehensive actions to protect the biodiversity, an important aspect for the conservation of these environments.

Biological interactions are also important structuring factors for the communities in these formations. For example, algae, marine angiosperms, sponges and corals play an important role as "ecosystem engineers", harboring several species of associated fauna (Barros & Rocha-Barreira, 2013; Barros *et al.*, 2013; Cavalcante *et al.*, 2014; Eggertsen *et al.*, 2017; Franklin Jr., 1992; Rocha-Barreira *et al.*, 2017). In particular, the dominance by macroalgae makes phytal communities an important component of the intertidal biota (Veras, 2011; Veras; Martins & Matthews-Cascon, 2013).

Nevertheless, despite the importance of primary producers, there are no productivity estimates, neither primary nor secondary, for these environments. A single study evaluated the net growth of the red alga *Gracilaria domingensis* in the MHE of Guajiru beach in the municipality of Trairi (Pinheiro-Joventino & Bezerra, 1980). The authors observed an increase in height of about 1.5% per day, with the population reaching a maximum length of 30 cm in about five months. This growth rate is not particularly high, especially when compared to that observed in controlled environments (Guimarães; Plastino & Oliveira, 1999). But it indicates an active development of the population, with probable reproduction throughout the year (Pinheiro-Joventino & Bezerra, 1980). In addition, at least part of the difference between gross growth (obtained in the laboratory) and net growth (observed in the field) may be due to herbivory (Hay; Colburn & Downing, 1983).

Regardless the important geographical differences in the level of knowledge about MHE, the assembly rules of epilithic intertidal communities are still poorly understood at the global level (Ingólfsson, 2005; Underwood, 2000). The MHE of Ceará are no exceptions. There appears to be strong competition for space in these formations (Barros *et al.*, 2013; Rabelo, 2007; Rabelo; Soares & Matthews-Cascon, 2013). However, coexistence mechanisms also occur (Rabelo; Soares & Matthews-Cascon, 2013) and the relative importance of the competition processes in the structuring of local communities is still not clear. Furthermore, information on the intensity of predation and herbivory pressure in these ecosystems is still lacking. There are documented records of predation in these areas (Meirelles & Matthews-Cascon, 2016; Santana *et al*., 2009) and the MHE often sustain a fauna known to exhibit numerous feeding strategies (carnivorous, herbivorous, detritivorous and omnivorous) (Feitosa & Araújo, 2002). But there are no data on the influence of this predation on the spatial variability of the biological communities. Lastly, the structure of these communities has not yet been adequately investigated from the functional point of view, which includes variables related to the functioning of the ecosystems, such as the space of the functional attributes or the degree of functional redundancy. Therefore, we still lack basic information on many aspects of the ecology of coastal MHE of Ceará. New efforts are thus urgently needed to fill these knowledge gaps, in order to safeguard these ecosystems against environmental impacts.

Economic importance

MHE are essential sources of ecosystem goods and services for coastal areas (Elliff & Kikuchi, 2017; Silva & Nascimento, 2020; Woodhead *et al*., 2019). It is possible to represent this importance numerically by integrating the values of direct and indirect uses, the possibility of future use, and the value of non-use of these ecosystems, in an estimate of the total economic value of these environments (Carneiro *et al*., 2017) (Table I). However, in the case of Ceará, few studies have addressed coastal MHE from an economic point of view (Maia & Rocha-Barreira, 2008), and there is no numerical survey of production in these environments. Only one study has sought to quantify in monetary terms the importance of this type of ecosystem in the state (Carneiro *et al*., 2017). This study, however, did not focus on the intertidal MHE, but on the submerged formations that make up the Pedra da Risca do Meio Marine State Park, located 18 km from the city of Fortaleza, in waters up to 30 m deep. According to Carneiro *et al.* (2017), the Park's subtidal MHE are worth about R$ 1 million per year mainly due to the services they provide to tourism and fishing and thus their degradation would bring significant losses to Ceará.

Table I – Main environmental goods and services provided by coastal marine hardbottom environments of Ceará and the type of associated economic value. The sum of all these values is equal to the total economic value of these environments

Type of Value	Environmenatl Goods and Services
Value of direct use	Tourism, fishing, recreation, education
Value of indirect use	Protection of the coastal zone, support to the biota
Value of future use	Economic potentials still unexplored, possibility of scientific discoveries
Value of no use	Preservation of the habitats and of the associated biodiversity, legacy for future generations

Although there are no value estimates, shallow and intertidal MHE on the Ceará coast are also targeted by tourists and fishermen. A large part of the tourist activity in the state is concentrated on the coast (Araujo, 2011; Vasconcelos & Coriolano, 2008), and it often happens in the vicinity of the rock formations. These MHE can constitute points of interest for divers and nature enthusiasts. However, unlike other Brazilian states, the MHE of Ceará does not usually fit among the main tourist attractions (Cordeiro & Bastos, 2014; Moura-Fé, 2015). The exception may be the Jericoacoara promontory (Julio et al., 2013), which is already a prominent geosite on the Brazilian coast (Moura-Fé, 2015). Considering the scenic beauty of some of the formations in Ceará, there is certainly space for the development of sustainable tourism based on these environments.

On the other hand, fishing in coastal MHE is a consolidated activity in the state, targeting mainly fish, octopuses and crustaceans, and mainly aimed at leisure, aquarium hobby or consumption, although a significant number of fishermen can use these formations as a source of income (Maia & Rocha-Barreira, 2008). Fishing corrals are relatively common on rocky platforms (Figure 5). These structures are built in wood and act by trapping fish during high tides (Lucena *et al.*, 2013). Historically, these corrals had an important participation in the production of fish in the state (Paiva & Nomura, 1965), but there are no recent surveys of their production nor a quantification of the relative use of MHE as substrate for these constructions.

Figure 5 – Fishing corrals (highlighted in white) over the rocky substrate at the beach of Pedra Rachada, municipality of Paracuru, Ceará. Image of Maxar Technologies obtained via Google Earth

Benthic organisms can also be an important fishing resource in the coastal MHE of Ceará. The collection of sea cucumber *Holothuria grisea* is an important addition to the income of fishermen in the far west of the state, with just over 12 tons of the species being commercialized between 2015 and 2016 (Ponte & Feitosa, 2019). Macroalgae are another important resource from MHE, and their extraction was an important activity in the coastal zone until the mid-twentieth century (Marinho-Soriano, 2017). Today, algae extraction is secondary due to the depletion of natural beds (Marinho-Soriano, 2017). However, some cultivation initiatives have been established in the state, and these are usually associated with MHE, which act as a source of raw material (Reis; Castelar & Santos, 2017).

Historically, MHE in Ceará were used in civil construction. Spix and Martius (1828) mention that the “corals” of Ceará were used to manufacture lime and Hawkshaw (1875) states that arenites were used as paving stones. Of greater relevance was the use of the MHE in Fortaleza (particularly the Porto reef) as the structural base to the city port from the mid-19th century to the mid-20th century (Morais & Pinheiro, 2005). Currently, such uses do not occur on a large scale, but there are still reports of MHE rocks being used to support civil construction in some fishing communities of the state (Soares personal communication). In addition, qualifying and quantifying such past uses may establish the importance of these MHE for the history of Ceará.

Regarding indirect uses, protection of the coastal zone against erosion is one of the most recognized roles of coastal MHE (Danjo & Kawasaki, 2014; Diniz & Amaral, 2003). This role, however, remains little quantified in Ceará. Another potential indirect use is spawning and growth of species of economic interest. The MHE of Ceará are home to juveniles of many species of fish, such as the dog snapper (*Lutjanus jocu*) and the black grouper (*Mycteroperca bonaci*) (Bezerra *et al.*, 2017; Godinho & Lotufo, 2010), indicating that such ecosystems have an important role in the reproductive cycle of these organisms (Eggertsen *et al.*, 2017). Similarly, the life cycle of the red lobster (*Panulirus meripurpuratus*, former *P. argus*) and green lobster (*P. laevicauda*), which are among the main fishing targets in the state, depends heavily on the coastal MHE, because their life stage after larval settlement takes place in these environments (Cruz *et al.*, 2015). Previous studies have also proposed the existence of important exchanges of matter and energy (including species) between shallow- and deep-water MHE (Soares; Tavares & Carneiro, 2019). Therefore, these coastal rocky formations can help compose some of the Ceará fish stocks.

In respect of potential future uses, coastal MHE in Ceará have been used to prospect marine natural products, with some positive results already achieved (Ávila *et al.*, 2019a, 2019b; 2018, Costa-Lotufo *et al.*, 2006; 2018; Jimenez *et al.*, 2003; Pinto *et al.*, 2020; Takeara *et al.*, 2007). The discovery of new substances is of interest to many Ocean Economy sectors and the biotechnology of marine organisms has experienced rapid growth rates in recent decades (Ióca; Nicacio & Berlinck, 2018; Thompson *et al.*, 2018). In this regard, the MHE of Ceará may come to occupy a relevant position because they hold a good fraction of the state's marine biodiversity.

Environmental impacts and conservation actions

Despite their ecological and economic importance, MHE on the Ceará shore have received little legal protection and only a few have been included in protected areas. A Resolution (Nº 01 / 2005) by the State Environmental Council (COEMA) and a State Law (Nº 13,796 / 2006) institute the Coastal Management Policy and Plan, which recognizes beachrocks as elements of the Ceará coastal landscape. However, these legislations do not provide measures to protect these MHE and specifically refer to sandstones cemented by calcium carbonate (i.e., beachrocks), thus excluding other types of rocky outcrops on Ceará beaches.

In Ceará most coastal MHE are of inorganic constitution. However, they are still susceptible to numerous environmental impacts and thus need legal protection. First, it is necessary to recognize that these environments sustain a large biodiversity, which still needs to be better characterized (Matthews-Cascon & Lotufo, 2006; Rocha-Barreira *et al.*, 2017). Then, it should be noted that coastal MHE are subject to weathering and the biological components are important for the maintenance of the rocky substrates, because they can mitigate erosive processes (Amaral & Bezerra, 2006; Bezerra *et al.*, 2005). In addition, the sediment dynamic along the coast, which generate cycles of burial and exposure of these formations, can also protect them from erosion and contribute to preserve their integrity (Barros, 2005). Lastly, some of these rocks may still be undergoing diagenesis and are at risk of incorporating pollutants into their matrix, which could weaken their structure (Arrieta *et al.*, 2017). Therefore, environmental stressors that interrupt geological and biological processes along the coast threatens the integrity of these ecosystems, compromising the provision of environmental goods and services.

Numerous environmental stressors affect coastal MHE in Ceará (Portugal *et al.*, 2016). Regarding the direct economic uses of these formations, the impacts of tourism, such as the trampling of the substrate, still need to be better evaluated in the state, despite being a cause for concern elsewhere (Santos *et al.*, 2015). On the other hand, there are records of serious impacts caused by the extractivism of benthic organisms. The intense seaweed harvesting during the 1970s led to the depletion of macroalgae stocks and the collapse of production from the 2000s onwards (Durairatnam, 1989; Marinho-Soriano, 2017; Reis; Castelar & Santos, 2017; Simioni; Hayashi & Oliveira, 2019). Currently, most macroalgae production in Ceará comes from farming (Marinho-Soriano, 2017). However, these seaweed farms often depend on raw material extracted from MHE, what may still put some pressure on the natural algae beds of the state (Marinho-Soriano, 2017; Reis; Castelar & Santos, 2017; Simioni; Hayashi & Oliveira, 2019). To prevent the case of macroalgae from repeating with other organisms, it is necessary to monitor and inspect the fishing activities in MHE, including because these ecosystems sustain the juveniles of many species of economic interest. Actions are also needed to replenish fishing stocks, to produce better estimates of the size and carrying capacity of these resources, and to develop more sustainable harvesting methods.

The historical use of MHE to support port activities has also had significant impacts on these ecosystems. In the case of Fortaleza, such use led to the severe degradation of the old Porto reef (Hawkshaw, 1875; Waring, 1914). The construction of a second large port in the state, the "Porto do Pecém", also increased siltation and introduced pollutants into rocky environments in the municipality of São Gonçalo do Amarante (Freitas; Vieira & Araújo, 2009). These impacts can be considered part of the processes of artificialization of the coastal zone of Ceará, which has intensified since the 20th century (Paula, 2015). This urbanization led to changes in coastal landscapes, impacting the dynamics of sediments and nutrients on the coast (Scherner *et al.*, 2013) and modifying patterns of substrate colonization (Pinheiro-Joventino; Barbosa & Dantas, 2000), which has already caused changes in the composition of benthic assemblages (Dantas *et al.*, 2005; Franklin Jr. *et al.*, 2005) and a considerable loss of species in the MHE of coastal Ceará (Portugal *et al.*, 2016).

More specifically, in addition to the negative impacts on biodiversity, the port development in Fortaleza intensified coastal erosion west of the city (Paula, 2015). This caused the exposure of new rocky substrates and may have contributed to an increase in the area of MHE in Ceará (Morais, 1980). On the other hand, this exposure also increased weathering of such formations and as a consequence intervention were required to protect the coastline, what further increased the presence of artificial structures along the shore (Paula, 2015). Furthermore, with the need to recompose eroded beaches (Lima, 2002), these formations once again faced the risk of being buried, this time by human action. This sequence of changes in the coastal environment may have had serious negative consequences on the dynamics of these ecosystems, but qualitative or quantitative measures of these impacts are still lacking.

Urbanization processes in the Ceará coastal zone also exposed MHE to pollution (Portugal *et al.*, 2016). In Fortaleza, this can include several types of contaminants (Buruaem *et al.*, 2012; Cavalcante *et al.*, 2010; Vieira *et al.*, 2011), which in general can have a negative effect on biological communities (Portugal *et al.*, 2016; Scherner *et al.*, 2013). However, due to the connectivity of marine environments, it is possible to observe waste such as plastic debris in abundance even far from large urban centers (Marques, 2017). These debris still caused no evident changes in the biota of coastal MHE (Marques, 2017), but they are known to negatively affect and increase the mortality of some reef species (Nunes *et al.*, 2018). In addition, their presence also suggests a possible occurrence of microplastic contamination (Marques, 2017). These small plastic fragments are known to accumulate around MHE possibly threatening the biota (Pinheiro *et al.*, 2019), however their impacts are still poorly understood worldwide.

From a purely biological point of view, another risk factor for MHE in the state is the introduction of exotic species. So far, at least six alien species have been introduced in the coastal zone of Ceará, five of which are marine invertebrates (Miranda; Freire & Matthews-Cascon, 2013; Soares; Davis & Carneiro, 2016) and one bony fish (Machado *et al.*, 2015). In addition, four other invertebrate species recorded in the state are currently considered cryptogenic (Miranda; Freire & Matthews-Cascon, 2013). Among these introduced and cryptogenic species, all but three (the gray shrimp *Penaeus vannamei* and the sun corals *Tubastrea tagusensis* and *T. coccinea*) were found in natural MHE. There are still no assessments of the situation of these populations (whether they are really established or not) or of the possible impacts caused by them. However, as the number of exotic species is already relevant, and may still increase in the future, it is necessary to monitor these organisms and establish well-founded management and conservation actions.

It is still necessary to consider that all these local stressors can act in synergy with global impacts. Heat anomalies, which are becoming more common in the state (Andrade *et al.*, 2012), have deleterious effects on local populations, and coral and zoanthid bleaching have already been recorded in Ceará (Soares & Rabelo, 2014). As these species are already naturally exposed to extremes of heat, any additional temperature rises could have a serious impact on the health of these populations. The influence of other factors, such as an increase in the supply of nutrients to the coast, changes in the rainfall regime, an increase in sea level, a higher incidence of storm waves (*swell*), and a decrease in the pH of the ocean water still need to be better evaluated *in loco*. But, by analogy with other locations and ecosystems, it is expected that they will also cause considerable damage to the fauna and flora of MHE in Ceará (Coutinho *et al.*, 2016; Leão *et al.*, 2016; Soares; Tavares & Carneiro, 2019).

Despite the lack of more comprehensive studies, there are signs that the combined action of environmental stressors has been causing gradual changes in the biological communities of MHE in Ceará. The last few decades have shown a significant increase in the abundance of constructions by the polychaete *Phragmatopoma* sp. This species was registered in the state from the early 2000s, associated with the pillars of the recently built Pecém Port in the municipality of São Gonçalo do Amarante. Since then, it has been observed in other locations and today they make up important structures on MHE in the state (Freitas *et al.*, 2019). In addition, biodiversity losses have been recorded in these environments (Portugal *et al.*, 2016). A relevant example is the probable local extinction of the sea urchin *Lytechinus variegatus*, an important herbivore in the lower intertidal and shallow subtidal zones. The species was the most abundant echinoid in the region until 2003 but has since disappeared from most of coastal Ceará. Lastly, the composition of the benthic assemblages in the majority of the MHE in Fortaleza, which is the largest city and urban area in Ceará, is already notably distinct from the others in the state (Dantas *et al.*, 2005; Franklin Jr. *et al.*, 2005). Therefore, such ecosystems have been suffering relevant environmental pressures, which puts at risk a rich biota and the provision of relevant environmental goods and services. More definitive conservation actions aimed at these environments are thus urgently needed.

CONCLUDING REMARKS

Beaches of Ceará are home to extensive and widely distributed rock formations. These structures have diverse geologic composition and origin, hold significant biodiversity, and have a particular ecological dynamic. In addition, they are a source of environmental and economic goods and services for the state. However, they suffer from environmental impacts and no conservation initiatives exist specifically to protect these ecosystems on any level of government (municipalities, states, and the federal government).

There are still many gaps in the knowledge about these ecosystems, which must be addressed so that MHE of Ceará can be used and managed properly. In the absence of these studies, it is prudent to adopt a cautious stance and assume that such environments are sensitive and are threatened by various local and global stressors. Future studies should be based on broader description schemes. For example, the functioning of coral reefs is characterized by eight complementary processes: calcium carbonate production and bioerosion, primary production and herbivory, secondary production and predation, and nutrient uptake and release (Brandl *et al.*, 2019). Investigating such processes in the MHE of Ceará would be essential for the qualification and quantification of the environmental goods and services provided by them. This would be a fundamental first step towards their long-term conservation.

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