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Marine carbonate mining in the Southwestern Atlantic: current status, potential impacts, and conservation actions

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ABSTRACT

Marine carbonate sediments have economic value because of their high concentration of calcium minerals and important trace elements. However, increasing mining interest in these stocks is threatening unique ecosystems, such as rhodolith beds, which provide many ecosystem goods and services. We review the potential of the unexplored Brazilian deposits and the rising conflicts with other blue economic sectors and biodiversity hotspots. The tropical Southwestern Atlantic Ocean, particularly the Brazilian Exclusive Economic Zone, has the largest deposit of marine limestone worldwide, which is very attractive to the global industry, with reserves measured at more than 1355,157,240 tons of $CaCO_3$ and it is especially useful as a supply for agriculture and animal nutrition. This large mining potential raises concerns regarding licenses and potential impacts, especially considering the biological and socio-economic importance of extensive rhodolith beds, which may conflict with mining. Additionally, future dredging activities will take place in vulnerable ecosystems without adequate marine spatial planning (MSP). Currently, there is no long-term scientific information on the available carbonate stocks, stock recoverability, risks to connectivity with other ecosystems (e.g., coral reefs), and the reduced provision of ecosystem services which may affect activities such as artisanal fisheries. In this context, encouraging carbonate mining without science-based information and MSP accelerates the unsustainable exploitation of this important ecosystem. This activity will contribute to the degradation of tropical marine biodiversity and threaten the food security of traditional and vulnerable human communities, which is in opposition to the Sustainable Development Goals and reaching the 2030 United Nations Agenda.

1. Introduction

Marine carbonate sediments are formed by sand and gravel that originate from fragments of calcareous algae, algal nodules, corals, mollusks, foraminifera, and benthic bryozoans that have high levels of calcium carbonates, magnesium, and other important trace elements [1,2]. A large portion of these sediments is formed by rhodoliths, which are free-living algal nodules composed partly or completely of non-geniculate calcareous red algae, which are considered habitat-forming species [3–6]. The use of algae has been known to have occurred since at least the 18th century [7,8] and has been successfully used by the European civilizations [9], for agriculture and horticulture

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as a soil conditioner or animal food additive, and in pharmaceutical and cosmetic products [10]. Although it is not a new product, in recent years, owing to the advent of deeper, low-cost, and modern mining technologies, these deposits have gained attention as a source of calcium carbonate, especially for uses in agriculture, animal nutrition, the cosmetic and medical industries, water treatment, and as a source of magnesium and trace elements [1]. All of these uses are growing worldwide, consequently increasing the pressure on the stocks, such as rhodoliths [1].

Rhodolith beds represent an important source of limestone, which has attracted the interest of mining companies, especially in shallow waters. However, rhodolith beds constitute a complex three-dimensional seascape, providing niches and habitat for a diversity of biota [11–13], which encompasses infaunal [14,15], epifaunal [15–17], and mobile assemblages [18] (Fig. 1). Moreover, rhodolith beds provide important ecosystem goods and services, acting as reef nursery areas, fishing grounds, and carbon stocks [18–20].

Rhodoliths represent one of the largest deposits of carbonate in the southwestern Atlantic and worldwide [21]. These areas are under pressure because they have economic potential [22–25], especially in the poorly-known tropical areas. The ecological and socioeconomic importance of rhodoliths conflicts with the industry interest. Carbonate mining is a global trend and recently, has grown even more [8]. This is due to the advent of modern and low-cost technologies and the scarcity of terrestrial carbonate mining resources [26].

Rhodolith bed formation depends on the temperature, nutrient availability, turbidity, sediment dynamics, and hydrodynamics (e.g., waves) to sustain carbonate growth and their vitality [25,27,28]. Nevertheless, disturbances, such as mining and dredging activities (e.g., clam-shell), can be catastrophic due to environmental changes and may lead to habitat destruction by exploitation [29–31]. Therefore, knowledge of the biodiversity and ecosystem services of these seascapes is of utmost importance, especially in one of the richest banks worldwide, as is the case of the beds in the southwestern Atlantic Ocean.

Given the context above, this paper discusses the economic potential of carbonate mining and the potential conflicts with biodiversity hotspots and fisheries resulting from the exploitation of Brazilian rhodoliths. First, we discuss historical carbonate mining on the French continental shelf and the potential of the Brazilian deposits. This comparative perspective of mining in a developed European country can be used as an example of the potential consequences of rhodolith bed extraction on tropical coasts and in developing countries such as Brazil. Second, we highlight the biological and socio-economic importance of rhodolith beds, which may conflict with the mining. Then, we conduct a solution-based analysis of the urgent policy actions. In this regard, this study aims to review an important topic in the fields of the blue economy and ocean governance, especially in the context of the the Sustainable Development Goals of the 2030 Agenda.

2. Carbonate exploitation in the French continental shelf

Free-living or dead calcareous algae are popularly known as *Maerl* in France. France contains one of the largest and thickest deposits worldwide which is concentrated in Brittany [32,33]. The exploitation of limestone in France is quite an old practice and has been widely conducted unsustainably [33]. Although soil enrichment with algae has been conducted for a long time [13,33], their exploitation intensified in the second half of the 20th century with the advent of technologies and the modernization of motorboats and dredges [33].

The Glenan bank is the best-documented bank and has an exploitation history of more than 50 years [34–36]. After overexploitation, finding living calcareous algae banks is rare [33]. As a result of this extraction, the associated macrofauna are no longer recorded in sediment cores [31]. In another area (the Breton banks), there was a change in diversity, with the benthos changing from bivalves and suspension feeders to a muddy sand community dominated by omnivores and deposit feeders [7,34]. In 2000, the license for extraction in France was approximately 500,000 tons per year [37].

Rhodoliths are non-renewable resources [34] as they take many decades to grow and the extraction rates are not compatible with their recovery rates. Consequently, extraction has a detrimental impact on habitat formation and the associated biological communities. In the case of French extraction, the rhodoliths undergo a wash during their extraction; consequently, the fine particles are released, causing impacts

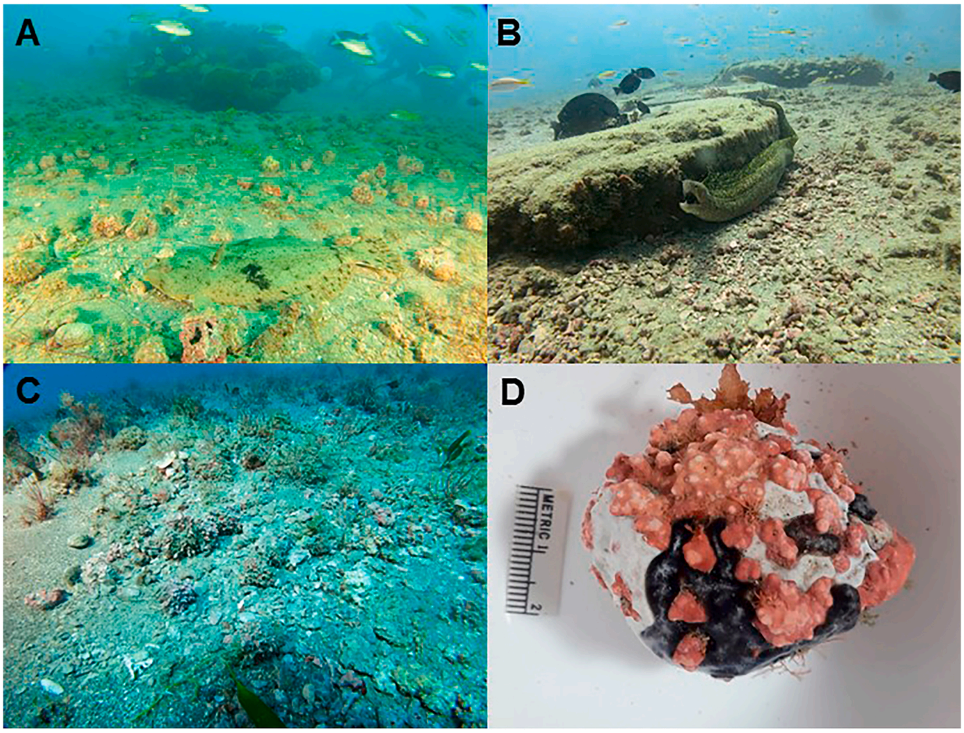

Fig. 1. The biodiversity that is associated with the complex three-dimensional seascape which is structured by rhodolith beds in the South Atlantic Ocean. (A, B) – Demersal fish associated with the rhodolith bottom (*Bothus* sp. and *Acanthurus chirurgus*), (C) - Epilithic macroalgae and seagrasses associated with rhodolith nodules, and (D) - A rhodolith nodule showing indented morphology housing ascidians (*Didemnum* sp. and *Trididemnum* sp.) and cryptic fauna.

Source: Marcus Davis Braga and Sandra Vieira Paiva.

such as the burial of the organisms or inhibition of photosynthesis due to increased turbidity [29,33] (Fig. 2). Since these algae are eco-engineers, their extraction has caused a reduction in biodiversity [38]. The impact of this exploitation led France to ban their extraction from 2011 [39], which may have been too late to allow for a full recovery. Rhodolith beds are listed in the European Red List of Habitats as vulnerable [40] and the Habitats Directive (Annex V); however, they still do not receive the attention they deserve considering their importance [33]. The ban on extraction in France [8] and parts of the United Kingdom [41] reduced pressure on rhodolith beds, but other European seabeds are not yet covered by an adequate extraction and exploitation plan [33]. Accordingly, they are under pressure and continue to decline [39]. Therefore, we could highlight what may happen in Brazil, which harbors a higher tropical biodiversity and large, unknown, and unexplored nearshore carbonate deposits.

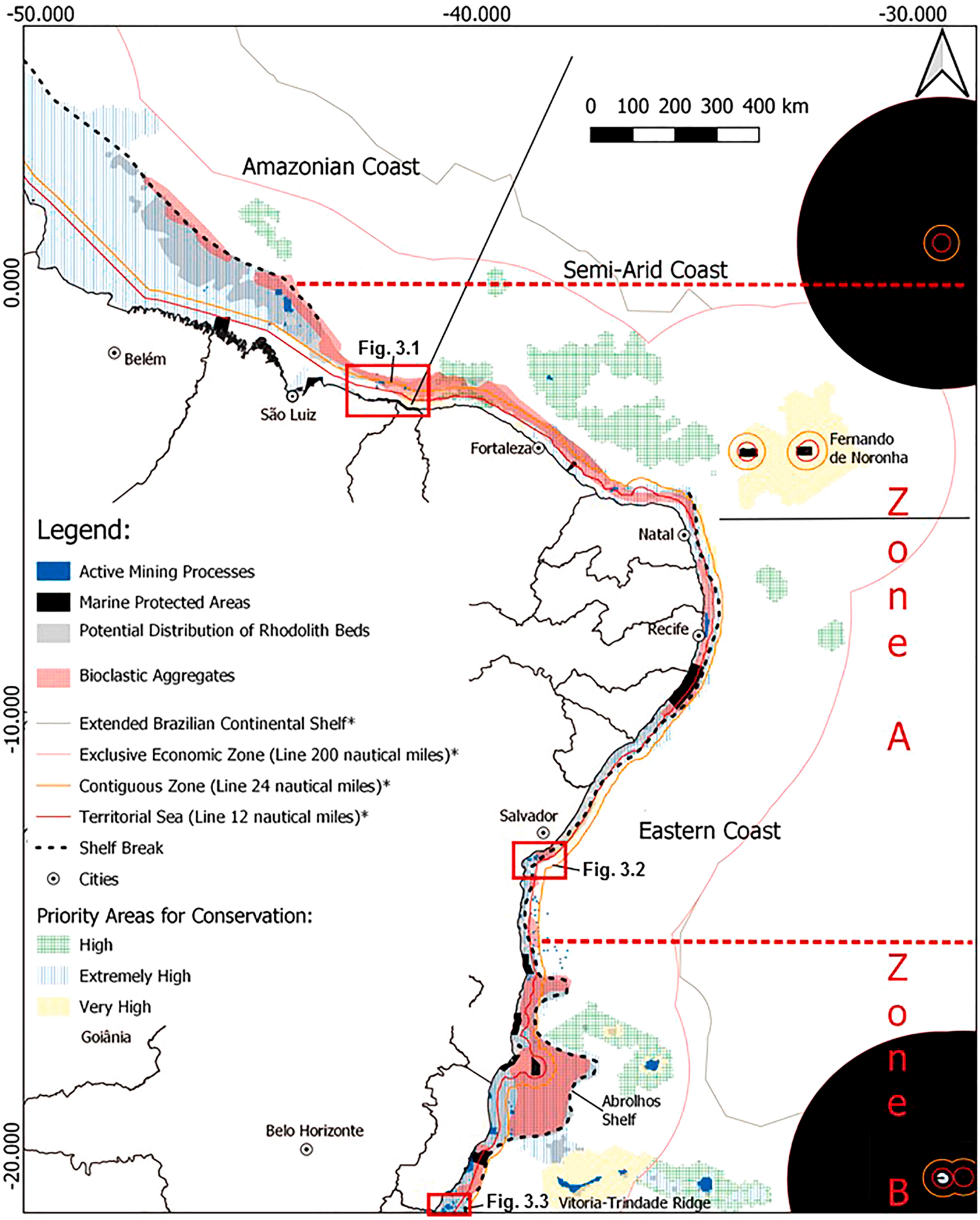

Fig. 2. Active mining processes, carbonate bottoms, and marine biodiversity hotspots along the Brazilian coast: the Amazonian shelf to the Vitoria-Trindade Ridge. This figure highlights active mining processes, marine protected areas, and priority areas for conservation [27,42-47]. Zones A and B refer to the classification system from Carannante et al. (1988) [48].
*Source - LEPLAC/ Brazilian Navy.

3. The potential marine carbonate mining areas in Brazil

The Brazilian shelf has the largest marine carbonate deposits worldwide, including rhodolith beds, which cover areas from the northern region (on the Amazon coast), crossing the northeast (tropical southwestern Atlantic) to the south of the Brazilian continental margin (temperate/subtropical) [48,49] over more than 4000 km. All of these regions have heterogeneous seabeds with the potential for the exploitation of carbonate [50–52]; however, most of these deposits are found in the North and Northeast regions (Fig. 3) and there are presently only low-resolution seafloor maps in large areas (although there are exceptions in small sectors as seen in Nascimento Silva et al. [53]; Ximenes Neto et al., [54]; Dias et al., [55]; and Morais et al. [56]), which makes a detailed understanding of these seascapes and their connectivity difficult. These typical tropical areas are found in the intertidal zone, crossing the shallow-mesophotic reef area (10–150 m deep) to a depth of 250 m in the rariphotic zone [57].

Potential areas for exploitation include the shallow-water and mesophotic rhodolith beds, which are unique seascapes for several reef species. It is also important to highlight that two rich areas are included: the Amazon Reefs, an ecological corridor between the South Atlantic and the Caribbean Sea [58,59], and the Abrolhos Bank, which is the richest and largest reef complex in the South Atlantic [21]. Both areas include endemics and reef species with socioeconomic importance for fisheries [8,21]. Furthermore, the North and Northeast Regions of Brazil have high levels of social inequality, poverty, and dependence on resources, such as fishing [60]. In this context, rhodolith beds play an important role in the provision of ecosystem services and food security [61].

The Brazilian continental shelf is formed by three zones (A, B, and C), classified according to the type of carbonates that are associated with the sediments and environmental conditions [48]. In Zone A (0–15° S; Fig. 2) both branching coralline algae and green algae (e.g., *Halimeda* spp.) predominate. In Zone B (15–23° S; Fig. 2), *Halimeda* algae are also present but the dominant algae are the reef-builders, coralline algae [62]. In contrast, in Zone C, in the subtropical/temperate region (23–35° S), the carbonate sediment is composed mainly of bioclasts such as mollusk shells, foraminifera, crustaceans, and echinoderms [48]. Due to this geological feature and biogenic sedimentary pattern, published research does not consider Zone C to have great potential for carbonate mining [1,8]. Therefore, we will mainly discuss tropical Zones A and B (Fig. 2) in this study.

The northernmost region, Zone A (Fig. 2), especially in the equatorial portion [63], has the largest coverage in the extent of known carbonate sediments since the 1960 s, consisting mainly of coralline and *Halimeda* algae, with a smaller contribution from mollusks, bryozoans, and foraminifera [49,51]. The continental shelf of Maranhão State (Figure 3.1) has abundant deposits of carbonate algae sediments, such as the banks of Tutóia, São Luis, Tarol, and Autoprofundo. They constitute valuable mining deposits [8,42] but are interconnected to the southernmost portion of the Amazon reefs [64], one of the largest and understudied mesophotic ecosystems in the South Atlantic.

In Ceará State, the shelf is divided into two areas according to the predominant algal type. The first area is located on the east coast (Fig. 2), where there is a predominance of *Halimeda* sand or gravel, followed by coralline algae, mollusks, and bryozoans [8,56]. This area

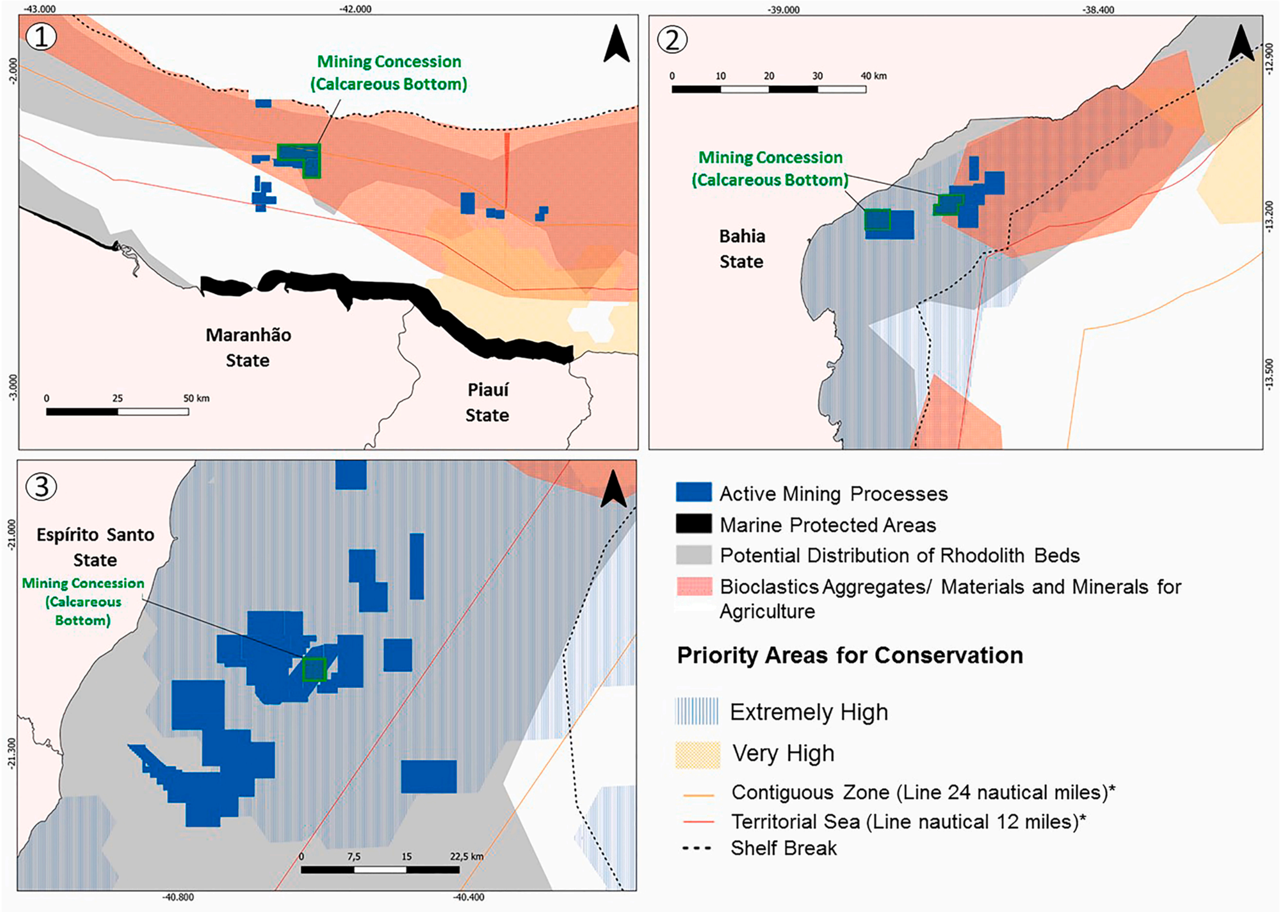

Fig. 3. The active process highlighting the mining concessions that overlap or are close to the rhodolith beds, marine protected areas, and priority areas for the conservation of the tropical marine biodiversity (South Atlantic, Brazil) [27,42-47]. (3.1) Maranhão and Piauí coast; (3.2) Bahia coast; and (3.3) Espírito Santo coast (South Atlantic, Brazil).

continues towards the Rio Grande do Norte State shelf, where a mixed zone of reef algal gravels, coralline algae, *Halimeda* algae, mollusks, foraminifera, and shallow-water and mesophotic reefs thrive [8,53,65]. The second area is the west coast, where coralline algae fragments and rhodolith nodules predominate, with the secondary accumulation of other organisms [8,65]. Therefore, from Maranhão State to Fortaleza City (Ceará State; Fig. 2), there is a large concentration of coralline algae and nearshore rhodolith beds in the shallow continental shelf [65,66], which has increased mining interest due to the lower economic costs for exploitation.

On the Eastern Brazilian coast, especially up to Sergipe State, there is a predominance of terrigenous sediments up to 20 m deep [8]. On the Bahia State shelf, coralline algae are predominant, especially in the rhodolith banks. The south coast of Bahia harbors the Abrolhos Region (Fig. 2 and Figure 3.2), which encompasses the largest continuous rhodolith bank worldwide, occupying an area of approximately 20, 902 km^2, similar to the area of the Great Barrier Reef in Australia [21]. The Espírito Santo coast (Brazilian tropical zone; Figure 3.3) also has extensive rhodolith beds, especially in the Vitória-Trindade Chain, which is rich in coralline algae [67]. Brazilian $CaCO_3$ deposits are estimated to be the largest worldwide [51,68], with a total of 2×10^{11} tons and a current lower estimate of extraction at 96,000–120,000 tons per year [69]. However, the reserves of marine carbonates that were measured and indicated for exploitation by the National Mining Agency are mostly distributed in the Bahia, Espírito Santo, Maranhão, and Piauí States [8] (Table 1), with a total of 1355,157,240 tons of $CaCO_3$.

It is important to note that Northeast Brazil (Zone A; Fig. 2) stands out for its abundant deposits and nearshore locations, with carbonate purity exceeding 75% [8]. Furthermore, the calcium carbonate in the rhodoliths is strategically best for extraction, as these rounded concretions facilitate dredging (e.g., clam-shell and suction) and the cost of separation is reduced owing to the low degree of mixing [1]. This represents a positive aspect from a mining perspective, greatly reducing operating costs, which increases profits. The exploitation of such carbonates is considered important by the Federal Government, as Brazil is a major world producer of agricultural food, but imports 75% of its fertilizer inputs [8].

Marine carbonates originate from organisms that consist of calcium carbonate, whereas terrestrial limestone has a geological origin. Thus, they differ in composition and are not completely substitutable [8]. Terrestrial limestone has the greatest application in correcting soil pH, whereas marine limestone is a high-quality fertilizer that is used to reduce the application of chemical fertilizers, increase agricultural productivity, and reduce production and importation costs [1,8]. Although the use of marine carbonates is recent in Brazil, they can be used in high-value industries such as agriculture (e.g., corn, beans, and fruits), the production of inputs for animal nutrition, shrimp farming, and water treatment [1]. In addition, these marine carbonates can represent an export product to Europe, where there is a reduction in banks due to long-term extraction, past impacts, and the prohibition of marine carbonate mining in France and England [8] which were discussed in Section 2.

3.1. The exploitation regulations for Brazilian seabeds

The extraction and licensing of live rhodoliths (the superficial layers) in Brazil is regulated by the normative instruction number 89 of 02/02/2006, which limits extraction to a maximum of 18 tons per company per year and is controlled by the Federal Environmental Licensing Agency (IBAMA) [70]. The Brazilian National Mining Agency (ANM) is responsible for regulating marine exploitation of the subsuperficial layer of rhodolith banks, which are considered mineral deposits, that is, non-living resources [8]. This criterion of separating the living and non-living resources seems to be clear; however, it is problematic because there are life forms associated with the subsuperficial rhodolith layer, such as live calcareous algae and associated cryptic biodiversity, which are not being considered [14].

Mineral legislation in Brazil is outdated and does not distinguish between mineral extraction in terrestrial or marine areas, which is a serious problem because activities in each of the environments have their particularities. Law n° 227/1967, known as the mining code in Brazil [71] and later modified by Law n° 9314/1996 [72] and Law n° 13.575/2017 [73], are the legal instruments that regulate aspects of mining. For marine exploitation, it is also necessary to have an exploitation permit that is issued by the ANM. Regarding the environmental aspects of exploitation, the IBAMA normative instruction, n°. 89/2006 [74], deals with the criteria which allow the exploitation, trade, and transport of live seaweed (which in this case includes rhodoliths), that which makes up the superficial layers of calcareous deposits, or seaweed arriving at the beach which is collected manually by fishers [74]. In the case of the subsurface layers, which are considered mineral deposits, their exploitation must meet the standards of the National Department of Mineral Production (now known as the ANM) according to the IBAMA ordinance n° 147/1997 and normative instruction n° 89/2006 [74,75].

Additionally, in terms of the mining activity, the environmental aspects that are legally protected are included in Law n° 6938/1981, the law of the National Environmental Policy [76], which contains the foundations of environmental protection in Brazil. Furthermore, IBAMA is responsible for licensing activities in the territorial sea, continental shelf, and exclusive economic zone, according to National Environmental Council resolution n° 237/1997 [77]. The Law n° 9605/1998 is the law on environmental crimes and states that damage will be considered and treated as an environmental crime with indemnity and imprisonment penalties [78]. In addition, Law n° 9985/2000 [79] and n° 4340/2002 were instituted by the National System of Conservation Units and cover environmental compensation in the case of the licensing of undertakings with significant impact [80]. These are legal tools that can be used to support marine protection in the case of the licensing of projects that may impact rhodolith beds (directly or indirectly). Despite this environmental legislation, there is weak implementation of the law and Brazil does not punish violators harshly. Furthermore, there is currently strong pressure to make laws more flexible in favor of economic growth, which would allow for increased impacts on marine biodiversity and is the result of the current (2018–2022) Brazilian Federal Government dismantling environmental policies [81].

Several applications have been filed or are in progress for the research and exploitation of these resources (Fig. 3). Moreover, some companies have already explored unique seabeds [8]. For instance, the

Table 1

Measured and indicated reserves of marine carbonates (tons) from the four states with the biggest CaCO3 concentrations in Brazil - Bahia, Espírito Santo, Maranhão, and Piauí (see Figs. 3 and 4 for the geographical locations).

Mineral reserves (t)					
	Bahia State	Espírito Santo State	Maranhão State	Piauí State	Total
Measured	9556,000	296,124,636	670,788,409	42,748,007	1019,217,052
Indicated	24,292,000	233,279,000	19,312,000	59,057,187	335,940,187
Total	33,848,000	529,403,636	690,100,409	101,805195	1355,157,240

Source: Cavalcanti (2020) [8].

most notable extraction activity of carbonates is occurring off the Espírito Santo State coast (Figure 3.3). In this state, a company managed to collect 73 tons of unprocessed calcareous algae at depths of around 15.5–28.5 m between 2002 and 2006 [67]. In particular, the Vitória-Trindade Seamount Chain (VTC) has attracted economic attention owing to its large rhodolith beds, despite being one of the most important biodiversity hotspots in the South Atlantic [67]. In 2011, the environmental licenses for extraction in the Davis Bank in the VTC were revoked due to irregularities in the mining extraction, since this seamount region is located in international waters [82], and thus the mining violated the treaty of the United Nations Convention on the Law of the Sea [8].

In Maranhão State (northeast Brazil; Figure 3.1), a mining company has been operating since 2014, extracting and processing the coralline algae for the fertilizer and animal nutrition industry [67] and in 2020 the company doubled its turnover to 60 million [83,84]. There are currently 12 mining concessions on the Brazilian continental shelf (Fig. 4), mostly in the Maranhão and Bahia States [8]. Also, the exploitation of this resource has been evolving, with an 80% growth in the sales value of marine limestone in Brazil between 2013 and 2018 (Table 2). Considering the extensive stocks which exist in Brazilian seabeds (Table 1), there is a high potential for mining expansion and gains from the exploitation of marine carbonates in shallower regions (Table 2); however, this possible growth will increase the threats to biodiversity and the ecosystem services, which are reviewed below.

3.2. *The threats to marine biodiversity and ecosystem services*

Rhodolith beds are ecosystems that are highly vulnerable to activities such as mining [20]. These banks provide food and a cryptic refuge, for example, for fish at early life stages [66]. They also shelter a unique biodiversity, including reef fish [12,18], ascidians, sponges [12], polychaetes [14], mollusks [85], corals [12], echinoderms [86], and crustaceans [85,87]. Moreover, they act as seed banks for algal propagules and the larvae of invertebrates and vertebrates in other interconnected ecosystems [88], such as coral reefs [18].

Despite the ecosystem goods and services cited above, these seascapes are currently threatened by several processes, including climate change impacts, such as acidification, warming [65], and extreme events, such as storms and energetic waves [89]. Moreover, overfishing by bottom trawling acts in tandem with these impacts to deteriorate the health and function of this ecosystem [90,91]. An example of a ecosystem function is the importance of rhodoliths for nurseries and foraging for spiny lobsters (*Panulirus* spp.). The Brazilian spiny lobster, an important fish resource, is associated with calcareous beds and is the main resource for the fisheries sector in the Northeast Region [43,92]. The exploitation of these calcareous banks is, therefore, concerning as it is in opposition to the sustainable development goals including 1 (No Poverty), 2 (Zero Hunger), 8 (Decent Work and Economic Growth), 10 (Reduced Inequalities), and 14 (Life Below Water). In this region, lobsters already suffer from impacts due to flawed fisheries management and overfishing [93,94]. Thus, efforts are to restore lobster stocks and fisheries sustainability, including the protection of habitats for refuge and nurseries, such as rhodolith beds.

Table 2
The production (ton) and production value (R$) of marine limestone in Brazil between 2013 and 2018.

Year	Gross production (t)	Processed production (t)	Production value (R$)	Average selling price per ton (R $)
2013	20,045.70	10,986.45	6948,354.00	662.72
2014	20,595.00	13,597.11	9671,813.50	684.53
2015	26,662.30	22,152.22	18,561,207.88	767.31
2016	38,152.41	24,517.49	22,999,303.17	795.17
2017	40,222.50	35,520.97	36,180,411.71	964.60
2018	40,815.97	35,294.87	36,239,470.44	1015.93

Source:Source: Cavalcanti (2020) [8].

4. Conservation measures to address unsustainable mining of calcium carbonate in the Southwestern Atlantic

4.1. *Conservation measures already in place to preserve the rhodolith beds*

The science-based knowledge of the biodiversity and ecosystem services associated with southwestern Atlantic rhodoliths that was reviewed in this article indicates the importance of these seabeds for conservation, the risk to the food security and ecosystem services, and the biogeochemical cycles which are affected by climate change. These seabeds are dynamic in their structure and the growth rate, density, and production of $CaCO_3$ are not directly associated [21,27,65]. Therefore, the extraction rate is likely higher than the recovery rate of these banks. Thus, the extraction of these deposits is unsustainable to sustain over the mid- and long-term [8]. The IBAMA uses the precautionary principle to deny environmental licenses in vulnerable habitats, such as rhodolith beds. A recent example is the denial of offshore oil and gas activities on the Amazon coast, which could threaten unique mesophotic reefs and interconnected rhodolith beds [59].

Rhodolith banks are the main habitat on the flattened tops of some seamounts in the VTC; Fig. 2), such as the east Jaseur, Davis, and Dogaressa seamounts and on the insular platforms around the Trindade and Martim Vaz islands [95]. They are also abundant in the Abrolhos Region [96] and Fernando de Noronha Archipelago, which are the best known rhodolith banks to date [21,57,95]. These areas are considered biodiversity hotspots of high biological and socio-economic importance for conservation and human populations [97]. Moreover, most of these areas are now inside marine protected areas with heterogeneous levels of protection, from multiple-use that allows for carbonate mining (after licensing) to no-take zones with the prohibition of fisheries and

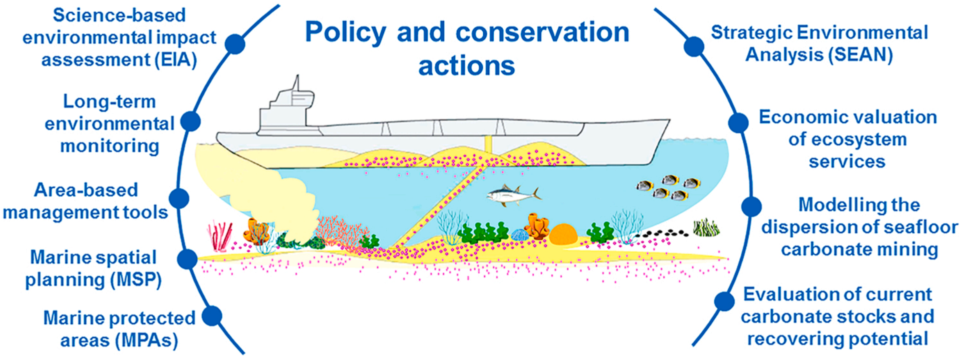

Fig. 4. Research, policy, and conservation actions for the rhodolith beds (Southwestern Atlantic, Brazil).

carbonate mining. These rhodolith beds are mobile reef environments [18,98], emphasizing once again the importance of these seascapes and the requirement for urgent and integral protection [85].

The Brazilian Northeast Region has extensive algae beds but knowledge of their structure, recovery potential, and long-term functioning is insufficient to allow for carbonate mining that is supported by science-based decisions [12]. Many Brazilian seabeds are also in mesophotic areas (over 30 m deep), which makes studying them infeasible, owing to the need for more financial resources to afford research vessels with more advanced technologies and improved logistics [12]. However, the extraction of these scarcely known areas will have large-scale knock-on effects, such as connectivity between the South Atlantic and the Caribbean Sea reef species. Mesophotic rhodolith beds are hotspots or oases for biodiversity [99] and are essential for connectivity between the West Atlantic reef habitats [18,59,98]. For example, a large population of the endangered macroalgae *Laminaria abyssalis,* a habitat-forming species [100], grows on rhodolith nodules in a mesophotic environment between 45 and 120 m in depth [50].

Most of these rhodolith beds are within the continental shelf, where multiple uses and conflicting interests already occur, such as oil and gas platforms, fishing grounds, bottom trawling areas, submarine cables, shipping lines, and renewable energy production [42,101] using offshore wind farms [102]. Particularly, in light of mining, this overlap has the potential for rising conflicts between these activities and an increase in the pressure on the South Atlantic beds in the coming years. In addition, Brazil has no marine spatial planning, which demonstrates a risk of multiple impacts on biodiversity and conflicts among different economic activities [103]. In the Brazilian socio-economic context, it is important to emphasize that artisanal fisheries are responsible for more than 50% of national fish production [104] and that mining activities increase the risk of food security in socioeconomically vulnerable populations that depend on small-scale fisheries (e.g., low-income populations) [105].

4.2. Research needs and tools

Rhodolith beds can provide insights into the distribution, biology, and ecology of various species [18]. More robust baseline studies are needed to predict the short-term and long-term impacts of activities, such as mining, on these beds, especially in the face of climate change. Technologies such as mixed-gas diving techniques, remotely operated underwater vehicle observations, bathymetric mapping, and side-scan sonar can help in understanding these environments, especially in the shallow and mesophotic beds. Considering that carbonate mining is a highly destructive and unsustainable human activity, it must be carefully studied to assess its levels of impact, duration, and frequency [106].

We need to understand which areas are less impacted than others, the extent and depth of the deposits, recovery potential, the distance of these deposits from the coast, and the associated communities. Studies that promote the economic exploitation of rhodolith banks in shallower regions are scarce and do not provide science-based support for sustainable extraction without significant social and biological impacts. This ongoing extraction in South America is analogous to the risk of deep-sea mining to biodiversity, ecosystem function, and related ecosystem services and the lack of equitable benefit sharing among the global community, now and for future generations [107]. There is a gap in the literature on the possibility of exploitation of these carbonates in the South Atlantic. Moreover, the impacts on these beds (and interconnected habitats such as reefs, seagrass beds, and mangroves) [18,66] and the strategies that should be adopted to recover these areas after extraction are largely unknown. There are no multidisciplinary and long-term studies to support the mining impacts on the southwestern Atlantic coastline; whereas similar studies were recently (2016) conducted by Europe (e.g., MIDAS project) to analyze the risks that are associated with deep-sea mining [108]. Although it brings short-term economic returns for a few enterprises, this type of exploitation is in opposition to the Sustainable Development Goals (Agenda 2030). The time that is required for extensive studies is insufficient for short-term decision-making [109].

4.3. Recommended short- and long-term actions

We highlight short- and long-term policy actions on conservation of rhodolith beds such as 1) Science-based environmental impact assessment (EIA) of carbonate mining projects; 2) Long-term environmental monitoring in rhodolith beds; 3) Implementation of Area-based management tools; 4) Marine spatial planning (MSP) along the Brazilian coast; 5) Creation of new no-take marine protected aereas (MPAs) to protect richest and vulnerable rhodolith beds; 6) Strategic Environmental Analysis (SEAN) to understand the areas available (or not) for mining exploitation; 7) Economic valuation of ecosystem services (e.g., fisheries) in rhodolith beds; 8) Modelling the dispersion of seafloor carbonate mining in exploitation areas; and 9) Evaluation of current carbonate stocks and recovering potential along the tropical Brazilian coast (Fig. 4).

The northern Brazil banks, Fernando de Noronha archipelago, and the Brazilian northeastern shelf-edge zone were indicated as ecologically and biologically significant areas by the Convention on Biological Diversity and high-priority areas for conservation [97,110] (Figs. 2 and 3). Rhodolith beds can also serve as stepping stones for many species. Therefore, the creation of no-take marine protected areas can be used for the preservation of rhodolith beds and as one of the best measures for the maintenance of reef biodiversity and ecosystem services, such as artisanal fisheries [111,112]. However, effective conservation actions must be integrated with other sectors of the blue economy and society, such as the mining industry, universities, and coastal communities, through the development of marine spatial planning (MSP). To date, Brazil does not have marine spatial planning on a national or regional scale [103]. Nevertheless, MSP is essential for preserving areas of ecological and socio-economic importance, such as rhodolith beds.

It is important to consider that since the Rio + 20 Conference, Brazil has been committed to the conservation of tropical oceans and is a signatory to global goals and agreements, such as the Convention on Biological Diversity and the United Nations Sustainable Development Goals. Despite these political commitments, there was no moratorium on carbonate mining licensing in these vulnerable hotspots in the South Atlantic. Therefore, it would be better to use the precautionary principle and avoid any carbonate mining (i.e., a moratorium) on the Brazilian tropical continental shelf until baseline and long-term oceanographic research provide sufficient science-based data to support decision-making by multiple stakeholders. This is important to avoid unpredictable risks to artisanal fisheries, such as their food security, and to sustain the ecosystem services that are worth a billion dollars in the tropical reef systems [113].

The rhodolith beds are areas of occurrence of socioeconomic importance species (Supplementary Information 1 – Table S1), such as the species of groupers of the subfamily Epinephelinae - *Epinephelus morio* and *Mycteroperca bonaci*. These species are important fishing resources, mainly for fishing production in the Brazilian Northeast [114]. They are species vulnerable to overfishing, including due to biological characteristics of the species itself, such as late maturation and reproduction [115], and the destruction of areas where the species occurs, such as rhodolith beds. Despite the lack of current economic valuation of ecosystem services on rhodolith beds the presence of reef species (Table S1) in Brazil [18] and other regions worldwide demonstrates a high economic value of their ecosystem services. Similarly, tropical reefs have increased in estimated value from around 8000 to around 352,000 $/ha/yr [113]. Future research need to evaluate the economic valuation of the ecosystem services of the rhodoliths to enable a better understanding of the socioeconomic gains from their conservation.

5. Conclusions and final remarks

The world's seabeds are a rich reservoir of mineral resources, and the southwestern Atlantic has great potential of carbonate resources in its Exclusive Economic Zone. Therefore, exploiting rhodoliths to obtain carbonates may seem promising for the mining and agriculture industry, since Brazil is one of the top world producers in this activity. Nevertheless, it may have devastating consequences on biodiversity and nearshore ecosystem services. Rhodoliths offer numerous ecosystem goods and services, including climate regulation, carbon sequestration, nutrient cycling, shelter, and protection for several reef species, including endemic species, and reproduction and nurseries for species of ecological and socio-economic interest. These banks could be more economically valuable when conserved rather than exploited, especially considering their importance in climate change mitigation and food security for artisanal fishers.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2022.105435.

References

[1] G.T.M. Dias, Granulados bioclásticos-algas calcárias, Rev. Bras. Geofis 18 (2000) 307–318, https://doi.org/10.1590/s0102-261x2000000300008.

[2] L.S. Pinheiro, A.R. Ximenes Neto, D.H.M. Medeiros, P.R.S. Pessoa, J.O. Morais, A plataforma continental semiárida do Brasil, in: D. Muehe, F.M. Lins-de-Barros, Ld.S. Pinheiro (Eds.), Geogr. Mar. Ocean. e Costas Na Perspect. Geógrafos, 2020, p. 764.

[3] J.E.S. Broom, D.R. Hart, T.J. Farr, W.A. Nelson, K.F. Neill, A.S. Harvey, W. J. Woelkerling, Utility of psbA and nSSU for phylogenetic reconstruction in the Corallinales based on New Zealand taxa, Mol. Phylogenet. Evol. 46 (2008) 958–973, https://doi.org/10.1016/j.ympev.2007.12.016.

[4] J. Halfar, B. Riegl, From coral framework to rhodolith bed: sedimentary footprint of the 1982/1983 ENSO in the Galápagos, Coral Reefs 32 (2013) 985, https://doi.org/10.1007/s00338-013-1058-5.

[5] R. Riosmena-Rodríguez, Natural history of rhodolith/maërl beds: their role in near-shore biodiversity and management, in: R. Riosmena-Rodríguez, W. Nelson, J. Aguirre (Eds.), Rhodolith/Maërl Beds A Glob. Perspect, 2017, pp. 3–26, https://doi.org/10.1007/978-3-319-29315-8_1.

[6] M.S. Foster, L.M. McConnico, L. Lundsten, T. Wadsworth, T. Kimball, L.B. Brooks, M. Medina-López, R. Riosmena-Rodríguez, G. Hernández-Carmona, R. M. Vásquez-Elizondo, S. Johnson, D.L. Steller, Diversidad e historia natural de una comunidad de *Lithothamnion muelleri* y *Sargassum horridum* en el Golfo de California, Cienc. Mar. 33 (2007) 367–384, https://doi.org/10.7773/cm.v33i4.1174.

[7] J. Cabioch, Les fonds de maerl de la baie de Morlaix et leur peuplement végétal, Cah. Biol. Mar. 10 (1969) 139–161.

[8] V.M.M. Cavalcanti, O Aproveitamento de granulados bioclásticos marinhos como alternativa para a indústria de fertilizantes no Brasil, 2020. [title translation in English: The use of marine bioclastic granulates as an alternative for the fertilizer industry in Brazil].

[9] G. Coletti, D. Basso, A. Frixa, Economic importance of coralline carbonates, in: R. Riosmena-Rodríguez, W. Nelson, J. Aguirre (Eds.), Rhodolith/Maërl Beds A Glob. Perspect, 2017, pp. 87–101, https://doi.org/10.1007/978-3-319-29315-8_4.

[10] G. Blunden, W.W. Binns, F. Perks, Commercial collection and utilisation of maërl, Econ. Bot. 29 (1975) 141–145, https://doi.org/10.1007/BF02863313.

[11] D. Basso, L. Babbini, S. Kaleb, V.A. Bracchi, A. Falace, Monitoring deep Mediterranean rhodolith beds, Aquat. Conserv. Mar. Freshw. Ecosyst. 26 (2016) 549–561, https://doi.org/10.1002/aqc.2586.

[12] M.S. Foster, G.M. Amado Filho, N.A. Kamenos, R. Riosmena-Rodriguez, D. L. Steller, Rhodoliths and rhodolith beds, Smithson. Contrib. Mar. Sci. 39 (2013) 143–155.

[13] J. Grall, M. Glémarec, Biodiversité des fonds de Maerl en Bretagne: approche fonctionnelle et impacts anthropiques, Vie Milieu 47 (1997) 339–349.

[14] C.S.G. Santos, J.B. Lino, Pd.C. Veras, G.M. Amado-Filho, R.B. Francini-Filho, F. S. Motta, R.L. de Moura, G.H. Pereira-Filho, Environmental licensing on rhodolith beds: insights from a worm, Nat. e Conserv. 14 (2016) 137–141, https://doi.org/10.1016/j.ncon.2016.06.002.

[15] D.L. Steller, R. Riosmena-Rodríguez, M.S. Foster, C.A. Roberts, Rhodolith bed diversity in the Gulf of California: the importance of rhodolith structure and consequences of disturbance, Aquat. Conserv. Mar. Freshw. Ecosyst. 13 (2003) 5–20, https://doi.org/10.1002/aqc.564.

[16] P.S. Brasileiro, G.H. Pereira-Filho, R.G. Bahia, D.P. Abrantes, S.M.P.B. Guimarães, R.L. Moura, R.B. Francini-Filho, A.C. Bastos, G.M. Amado-Filho, Macroalgal composition and community structure of the largest rhodolith beds in the world, Mar. Biodivers. 46 (2016) 407–420, https://doi.org/10.1007/s12526-015-0378-9.

[17] T. Dulin, S. Avnaim-Katav, G. Sisma-Ventura, O.M. Bialik, D.L. Angel, Rhodolith beds along the southeastern Mediterranean inner shelf: implications for past depositional environments, J. Mar. Syst. 201 (2020), 103241, https://doi.org/10.1016/j.jmarsys.2019.103241.

[18] R.L. Moura, M.L. Abieri, G.M. Castro, L.A. Carlos-Júnior, P.M. Chiroque-Solano, N.C. Fernandes, C.D. Teixeira, F.V. Ribeiro, P.S. Salomon, M.O. Freitas, J. T. Gonçalves, L.M. Neves, C.W. Hackradt, F. Felix-Hackradt, F.A. Rolim, F. S. Motta, O.B.F. Gadig, G.H. Pereira-Filho, A.C. Bastos, Tropical rhodolith beds are a major and belittled reef fish habitat, Sci. Rep. 11 (2021) 1–10, https://doi.org/10.1038/s41598-020-80574-w.

[19] L.H. Van Der Heijden, Calculating the global contribution of coralline algae to carbon burial, Biogeosciences 12 (2015) 7845–7877, https://doi.org/10.5194/bgd-12-7845-2015.

[20] P.A. Horta, G.M. Amado-filho, C.F.D. Gurgel, ReBentos Rhodoliths in Brazil: current knowledge and potential impacts of climate change, Braz. J. Oceanogr. (2016).

[21] G.M. Amado-Filho, R.L. Moura, A.C. Bastos, L.T. Salgado, P.Y. Sumida, A.Z. Guth, R.B. Francini-Filho, G.H. Pereira-Filho, D.P. Abrantes, P.S. Brasileiro, R.G. Bahia, R.N. Leal, L. Kaufman, J.A. Kleypas, M. Farina, F.L. Thompson, Rhodolith beds are major CaCO 3 BIO-factories in the tropical south West Atlantic, PLoS One 7 (2012) 5–10, https://doi.org/10.1371/journal.pone.0035171.

[22] G.M. Amado-Filho, G.H. Pereira-Filho, R.G. Bahia, D.P. Abrantes, P.C. Veras, Z. Matheus, Occurrence and distribution of rhodolith beds on the Fernando de Noronha Archipelago of Brazil, Aquat. Bot. 101 (2012) 41–45, https://doi.org/10.1016/j.aquabot.2012.03.016.

[23] G.M. Amado-Filho, G.H. Pereira-Filho, Rhodolith beds in Brazil: a new potential habitat for marine bioprospection, Braz. J. Pharm. 22 (2012) 782–788, https://doi.org/10.1590/S0102-695X2012005000066.

[24] B.V. Marins, G.M. Amado-Filho, M.B.B. Barreto, L.L. Longo, Taxonomy of the southwestern Atlantic endemic kelp: *Laminaria abyssalis* and *Laminaria brasiliensis* (Phaeophyceae, Laminariales) are not different species, Phycol. Res 60 (2012) 51–60, https://doi.org/10.1111/j.1440-1835.2011.00635.x.

[25] V. Testa, D.W.J. Bosence, Physical and biological controls on the formation of carbonate and siliciclastic bedforms on the north-east Brazilian shelf, Sedimentology 46 (1999) 279–301, https://doi.org/10.1046/j.1365-3091.1999.00213.x.

[26] L.M. Wedding, S.M. Reiter, C.R. Smith, K.M. Gjerde, J.N. Kittinger, A. M. Friedlander, S.D. Gaines, M.R. Clark, A.M. Thurnherr, S.M. Hardy, L. B. Crowder, Managing mining of the deep seabed, Sci. (80-.). 349 ((2015) 144–145, https://doi.org/10.1126/science.aac6647.

[27] V.F. Carvalho, J. Assis, E.A. Serrão, J.M. Nunes, A.B. Anderson, M.B. Batista, J. B. Barufi, J. Silva, S.M.B. Pereira, P.A. Horta, Environmental drivers of rhodolith beds and epiphytes community along the South Western Atlantic coast, Mar. Environ. Res. 154 (2020), 104827, https://doi.org/10.1016/j.marenvres.2019.104827.

[28] G.M. Dias, R.M. da Rocha, T.M. da, C. Lotufo, L.P. Kremer, Fifty years of ascidian biodiversity research in São Sebastião, Braz., J. Mar. Biol. Assoc. U. Kingd. (2012) 1–10, https://doi.org/10.1017/S002531541200063X.

[29] S. De Grave, The influence of sedimentary heterogeneity on within maerl bed differences in infaunal crustacean community, Estuar. Coast. Shelf Sci. 49 (1999) 153–163, https://doi.org/10.1006/ecss.1999.0484.

[30] J. Hall-Spencer, N. White, E. Gillespie, K. Gillham, A. Foggo, Impact of fish farms on maerl beds in strongly tidal areas, Mar. Ecol. Prog. Ser. 326 (2006) 1–9, https://doi.org/10.3354/meps326001.

[31] J.M. Hall-Spencer, P.G. Moore, Scallop dredging has profound, long-term impacts on maerl habitats, ICES J. Mar. Sci. 57 (2000) 1407–1415, https://doi.org/10.1006/jmsc.2000.0918.

[32] C. Augris, P. Berthou, Les gisements de maerl en bretagne, 1990.

[33] J. Grall, J.M. Hall-Spencer, Problems facing maerl conservation in Brittany, Aquat. Conserv. Mar. Freshw. Ecosyst. 13 (2003) 55–64, https://doi.org/10.1002/aqc.568.

[34] Biomaerl Team, BIOMAERL: Maerl biodiversity; Functional structure and anthropogenic impacts, 1999.

[35] G. Blunden, W.F. Farnham, N. Jephson, R.H. Fenn, B.A. Plunkett, The composition of maërl from the glenan islands of Southern Brittany, Bot. Mar. 20 (1977) 121–126, https://doi.org/10.1515/botm.1977.20.2.121.

[36] J.P. Pinot, Le precontinent breton entre penmarch, belle ile et' l escarpement continental, 1974.

[37] W.A. Nelson, Calcified macroalgae critical to coastal ecosystems and vulnerable to change: a review, Mar. Freshw. Res. 60 (2009) 787–801, https://doi.org/10.1071/MF08335.

[38] G. Bernard, A. Romero-Ramirez, A. Tauran, M. Pantalos, B. Deflandre, J. Grall, A. Grémare, Declining maerl vitality and habitat complexity across a dredging gradient: Insights from in situ sediment profile imagery (SPI, Sci. Rep. 9 (2019) 1–12, https://doi.org/10.1038/s41598-019-52586-8.

[39] OSPAR Commission, Guidance on the Development of Status Assessments for the OSPAR List of Threatened and/or Declining Species and Habitats (OSPAR Agreement 2019–05), 2019. ⟨https://www.ospar.org/documents?v=40966⟩.

[40] S. Gubbay, N. Sanders, T. Haynes, J.A.M. Janssen, J.R. Rodwell, A. Nieto, M. García Criado, S. Beal, J. Borg, M. Kennedy, D. Micu, M. Otero, G. Saunders, M. Calix, Eur. Red. List Habitats (2016), https://doi.org/10.2779/032638.

[41] J. Hall-spencer, Ban on maerl extraction - news, Mar. Pollut. Bull. 50 (2005) 121–124, https://doi.org/10.1016/j.marpolbul.2005.01.013.

[42] V.M.M. Cavalcanti, Plataforma Continental a últim fronteira da mineração brasileira, 2011. ⟨http://www2.dnpm.gov.br/mostra_arquivo.asp?IDBancoArquivoArquivo=5579⟩. [title translation in English: Continental shelf: the last frontier for Brazilian mining].

[43] Pd.N. Coutinho, J.O. de Morais, Distribucion De Los Sedimentos En La Plataforma Continental Norte Y Nordeste Del Brasil, Arq. Ciências Do Mar. 10 (1970) 79–90, https://doi.org/10.32360/acmar.v10i1.32703.

[44] K.G. Souza, L.R. Martins, V.M. Cavalcanti, C.V. Pereira, L.F. Borges. Recursos Não-Vivos da Plataforma Continental Brasileira e Áreas Oceânicas Adjacentes, Special edition, GRAVEL, Porto Alegre, 2009, pp. 1–86.

[45] MMA, Priority Areas for Conservation. https://www.gov.br/mma/pt-br/assuntos/servicosambientais/ecossistemas-1/conservacao-1/areas-prioritarias/2a-atualizacao-das-areas-prioritarias-para-conservacao-da-biodiversidade-2018.

[46] ANM, Active Mining Processes. https://geo.anm.gov.br/portal/apps/webappviewer/index.html?id=6a8f5ccc4b6a4c2bba79759aa952d908.

[47] ICMBIO, Marine Protected Areas. https://www.gov.br/icmbio/pt-br.

[48] G. Carannante, M. Esteban, J.D. Milliman, L. Simone, Carbonate lithofacies as paleolatitude indicators: problems and limitations, Sediment. Geol. 60 (1988) 333–346, https://doi.org/10.1016/0037-0738(88)90128-5.

[49] M.S. Foster, Rhodoliths: between rocks and soft places, J. Phycol. 37 (2001) 659–667, https://doi.org/10.1046/j.1529-8817.2001.00195.x.

[50] G. Amado-Filho, Structure of rhodolith beds from 4 to 55 meters deep along the southern coast of Espírito Santo State, Brazil, Cienc. Mar. 33 (2007) 399–410, https://doi.org/10.7773/cm.v33i4.1148.

[51] M. Kempf, Notes on the benthic bionomy of the N-NE Brazilian shelf, Mar. Biol. 5 (1970) 213–224, https://doi.org/10.1007/BF00346909.

[52] J.D. Milliman, Role of calcareous algae in Atlantic continental margin segmentation, in: E. Flugel (Ed.), Foss. Algae, Berlim, 1977: pp. 232–247.

[53] L.L. do Nascimento Silva, M.P. Gomes, H. Vital, The Açu Reef morphology, distribution, and inter reef sedimentation on the outer shelf of the NE Brazil equatorial margin, Cont. Shelf Res. 160 (2018) 10–22, https://doi.org/10.1016/j.csr.2018.03.011.

[54] A.R. Ximenes Neto, P.R.S. Pessoa, L. de, S. Pinheiro, J.O. Morais, Seismic stratigraphy of a partially filled incised valley on a semi-arid continental shelf, Northeast Brazil, Geo-Mar. Lett. 41 (2021), https://doi.org/10.1007/s00367-021-00687-7.

[55] G.T. de, M. Dias, R.Cd.O. Silva, J.R. dos Santos Filho, Manoel Luiz Reefs morphology unveiled by high resolution satellite images (North Brazilian Continental Shelf), Quat. Environ. Geosci. 12 (2021) 46–59, https://doi.org/10.5380/abequa.v12i1.76577.

[56] J.O. de Morais, A.R. Ximenes Neto, P.R.S. Pessoa, Ld.S. Pinheiro, Morphological and sedimentary patterns of a semi-arid shelf, Northeast Brazil, Geo Mar. Lett. (2019).

[57] M.C. Henriques, L.M. Coutinho, R. Riosmena-Rodríguez, M.B. Barros-Barreto, S. Khader, M.A.O. Figueiredo, Three deep water species of Sporolithon (Sporolithales, Rhodophyta) from the Brazilian continental shelf, with the description of Sporolithon elevatum sp. nov, Phytotaxa 190 (2014) 320–330, https://doi.org/10.11646/phytotaxa.190.1.19.

[58] G. Calegario, L. Freitas, L.R. Appolinario, T. Venas, T. Arruda, K. Otsuki, B. Masi, C. Omachi, A.P. Moreira, A.C. Soares, C.E. Rezende, G. Garcia, D. Tschoeke, C. Thompson, F.L. Thompson, Conserved rhodolith microbiomes across environmental gradients of the Great Amazon Reef, Sci. Total Environ. 760 (2021), 143411, https://doi.org/10.1016/j.scitotenv.2020.143411.

[59] R.B. Francini-Filho, N.E. Asp, E. Siegle, J. Hocevar, K. Lowyck, N. D'Avila, A. A. Vasconcelos, R. Baitelo, C.E. Rezende, C.Y. Omachi, C.C. Thompson, F. L. Thompson, Perspectives on the Great Amazon Reef: extension, biodiversity, and threats, Front. Mar. Sci. 5 (2018) 1–5, https://doi.org/10.3389/fmars.2018.00142.

[60] S.F. Câmara, F.R. Pinto, F.R. da Silva, Md.O. Soares, T.M. de Paula, Socioeconomic vulnerability of communities on the Brazilian coast to the largest oil spill (2019–2020) in tropical oceans, Ocean Coast. Manag. 202 (2021), https://doi.org/10.1016/j.ocecoaman.2020.105506.

[61] R. Araújo, F. Vázquez Calderón, J. Sánchez López, I.C. Azevedo, A. Bruhn, S. Fluch, M. Garcia Tasende, F. Ghaderiardakani, T. Ilmjärv, M. Laurans, M. Mac Monagail, S. Mangini, C. Peteiro, C. Rebours, T. Stefansson, J. Ullmann, Current status of the algae production industry in europe: an emerging sector of the blue bioeconomy, Front. Mar. Sci. 7 (2021) 1–24, https://doi.org/10.3389/fmars.2020.626389.

[62] M.N. Sissini, G. Koerich, M.B. de Barros-Barreto, L.M. Coutinho, F.P. Gomes, W. Oliveira, I.O. Costa, J.M. de Castro Nunes, M.C. Henriques, T. Vieira-Pinto, B. N. Torrano-Silva, M.C. Oliveira, L. Le Gall, P.A. Horta, Diversity, distribution, and environmental drivers of coralline red algae: the major reef builders in the Southwestern Atlantic, Coral Reefs (2021), https://doi.org/10.1007/s00338-021-02171-1.

[63] M.O. Soares, C.C. Campos, P.B.M. Carneiro, H.S. Barroso, R.V. Marins, C.E. P. Teixeira, M.O.B. Menezes, L.S. Pinheiro, M.B. Viana, C.V. Feitosa, J.I. Sánchez-Botero, L.E.A. Bezerra, C.A. Rocha-Barreira, H. Matthews-Cascon, F.O. Matos, A. Gorayeb, M.S. Cavalcante, M.F. Moro, S. Rossi, G. Belmonte, V.M.M. Melo, A. S. Rosado, G. Ramires, T.C.L. Tavares, T.M. Garcia, Challenges and perspectives for the Brazilian semi-arid coast under global environmental changes, Perspect. Ecol. Conserv 19 (2021) 267–278, https://doi.org/10.1016/j.pecon.2021.06.001.

[64] C.A.M.M. Cordeiro, J.P. Quimbayo, J.A.C.C. Nunes, L.T. Nunes, M.N. Sissini, C.L. S. Sampaio, R.A. Morais, P.A. Horta, A.W. Aued, J.L. Carraro, E. Hajdu, L. A. Rocha, B. Segal, S.R. Floeter, Conservation status of the southernmost reef of the Amazon Reef System: the Parcel de Manuel Luís, Coral Reefs 40 (2021) 165–185, https://doi.org/10.1007/s00338-020-02026-1.

[65] P.Bd.M. Carneiro, J.P. de Lima, Ê.V.P. Bandeira, A.R. Ximenes Neto, Cd.A. Rocha Barreira, F.Td.S. Tâmega, H. Matthews-Cascon, W. Franklin Junior, J.O. de Morais, Structure, growth and CaCO3 production in a shallow rhodolith bed from a highly energetic siliciclastic-carbonate coast in the equatorial SW Atlantic Ocean, Mar. Environ. Res. 166 (2021), https://doi.org/10.1016/j.marenvres.2021.105280.

[66] A.C.P.C. Costa, T.M. Garcia, B.P. Paiva, A.X. Neto, M.D.O. Soares, Seagrass and rhodolith beds are important seascapes for the development of fish eggs and larvae in tropical coastal area, Mar. Environ. Res. (2020), https://doi.org/10.1016/j.marenvres.2020.105064.

[67] G.M. Amado-filho, R.G. Bahia, G.H. Pereira-filho, L.L. Longo, South Atlantic Rhodolith Beds: Latitudinal Distribution, Species Composition, Structure and Ecosystem Functions, Threats and Conservation Status, in: R. Riosmena-Rodriguez, W. Nelson, J. Aguirre (Eds.), Rhodolith/Maerl Beds A Glob. Perspect., 2017: p. 29315. ⟨https://doi.org/10.1007/978–3-319–29315-8⟩.

[68] J. Milliman, C. Amaral, Economic potential of Brazilian continental margin sediments. Annals of 28, in: Ann. 28th Brazilian Congr. Geol., 1974: pp. 335–344.

[69] P. Riul, P.T. Visscher, P.A. Horta, Decrease in Lithothamnion sp. (Rhodophyta) primary production due to the deposition of a thin sediment layer, (2008). ⟨https://doi.org/10.1017/S0025315408000258⟩.

[70] IBAMA. Normative Instruction n° 89, Official Diary of the Union; 2006. Allow the exploration, exploitation, transport and distribution, including the resale, of seaweed from the Brazilian coast. (2006).

[71] Brazil. Decree -law no 1,985. Official Diary of the Union; 1967. Mining Code. (1967).

[72] Brazil. Law no 9,314, Official Diary of the Union; 1996. Amends provisions of Decree-Law No. 227 (Mining Code), of February 28, 1967, and takes other measures. (1996).

[73] Brazil. Law no 13,575, Official Diary of the Union; 2017. Creates the National Mining Agency (ANM); abolishes the National Department of Mineral Production (DNPM); amends Laws nº. 11,046, of December 27, 2004, and 10,826, of December 22, 2003; and revokes Law n°. 8,876, of May 2, 1994, and provisions of Decree-Law nº. 227, of February 28, 1967 (Mining Code). (2017).

[74] IBAMA (Brazilian Institute of the Environment). Normative Instruction n° 89, Official Diary of the Union; (2006).

[75] IBAMA (Brazilian Institute of the Environment). Ordinance n° 147, Official Diary of the Union; 1997. Provides for the exploration mission of natural seaweed fields by individuals or legal entities. (1997).

[76] Brazil. Law no 6,938, Official Diary of the Union; 1981. Provides for the National Environmental Policy, its purposes and mechanisms for its formulation and application, and makes other provisions. (1981).

[77] Brazil. Resolution CONAMA no 237. Official Diary of the Union; 1997. Provides for concepts, subjection, and procedure for obtaining Environmental Licensing, and other providences. (1997).

[78] Brazil. Law no 9,605, Official Diary of the Union; 1998. Dispõe sobre as sanções penais e administrativas derivadas de condutas e atividades lesivas ao meio ambiente, e dá outras providências. (1998).

[79] Brazil. Law no 9,985, Official Diary of the Union, 2000. Regulates art. 225, § 1, items I, II, III and VII of the Federal Constitution, establishes the National System of Nature Conservation Units and other provisions. (2000).

[80] Brazil. Decree no 4.340, Official Diary of the Union, 2002. Regulates articles of Law n°. 9,985, of July 18, 2000, which provides for the National System of Nature Conservation Units - SNUC, and other provisions. (2002).

[81] L.G. Barbosa, M.A.S. Alves, C.E.V. Grelle, Actions against sustainability: dismantling of the environmental policies in Brazil, Land Use Policy 104 (2021), 105384, https://doi.org/10.1016/j.landusepol.2021.105384.

[82] Y. Vasconcelos, Fertilizante marinho. Uso de algas calcárias como adubo em lavouras de cana, Pesqui. Fapesp. Julho (2012) 62–64. 〈http://revistapesquisa.fapesp.br/wp-content/uploads/2012/07/Pesquisa_197-21.pdf?f7d68e〉.

[83] R. Grisotto, Litoral do Maranhão escondia tesouro de algas marinhas, (2018) 1–9. 〈https://epocanegocios.globo.com/Empresa/noticia/2018/05/litoral-do-maranhao-escondia-tesouro-de-algas-marinhas.html〉.

[84] F. Lopes, Oceana eleva produção de exportação, (2020). 〈https://valor.globo.com/agronegocios/noticia/2020/03/13/oceana-eleva-producao-e-exportacao.ghtml?〉.

[85] Pd.C. Veras, I. Pierozzi-Jr, J.B. Lino, G.M. Amado-Filho, A.R. de Senna, C.S. G. Santos, R.L. de Moura, F.D. Passos, V.J. Giglio, G.H. Pereira-Filho, Drivers of biodiversity associated with rhodolith beds from euphotic and mesophotic zones: insights for management and conservation, Perspect. Ecol. Conserv 18 (2020) 37–43, https://doi.org/10.1016/j.pecon.2019.12.003.

[86] A.I. Gondim, T.L.P. Dias, R.Cd.S. Duarte, P. Riul, P. Lacouth, M.L. Christoffersen, Filling a knowledge gap on the biodiversity of rhodolith-associated Echinodermata from northeastern Brazil, Trop. Conserv. Sci. 7 (2014) 87–99, https://doi.org/10.1177/194008291400700112.

[87] C. Sánchez-Latorre, R. Triay-Portella, M. Cosme, F. Tuya, F. Otero-Ferrer, Brachyuran crabs (Decapoda) associated with rhodolith beds: Spatio-temporal variability at Gran Canaria Island, Diversity 12 (2020), https://doi.org/10.3390/D12060223.

[88] S. Fredericq, S. Krayesky-Self, T. Sauvage, J. Richards, R. Kittle, N. Arakaki, E. Hickerson, W.E. Schmidt, The critical importance of rhodoliths in the life cycle completion of both macro- and microalgae, and as holobionts for the establishment and maintenance of marine biodiversity, Front. Mar. Sci. 5 (2019), https://doi.org/10.3389/fmars.2018.00502.

[89] A. Lavenère-Wanderley, N.E. Asp, F.L. Thompson, E. Siegle, Rhodolith mobility potential from seasonal and extreme waves, Cont. Shelf Res. 228 (2021), https://doi.org/10.1016/j.csr.2021.104527.

[90] L. Teed, D. Bélanger, P. Gagnon, E. Edinger, Calcium carbonate (CaCO3) production of a subpolar rhodolith bed: Methods of estimation, effect of bioturbators, and global comparisons, Estuar. Coast. Shelf Sci. 242 (2020), https://doi.org/10.1016/j.ecss.2020.106822.

[91] E. Fragkopoulou, E.A. Serrão, P.A. Horta, G. Koerich, J. Assis, Bottom trawling threatens future climate refugia of rhodoliths globally, Front. Mar. Sci. 7 (2021) 1–11, https://doi.org/10.3389/fmars.2020.594537.

[92] J. Fausto-Filho, A.F. Costa, Notas Sobre a família Palinuridae no Nordeste Brasileiro (Crustacea, Decapoda, Macrura), Arq. Ciências Do Mar. 9 (1969) 103–110.

[93] R. Cruz, K.C.A. Silva, S.D.S. Neves, I.H.A. Cintra, Impact of lobster size on catches and prediction of commercial spiny lobster landings in brazil, Crustaceana 86 (2013) 1274–1290, https://doi.org/10.1163/15685403-00003230.

[94] R. Cruz, J.V.M. Santana, C.G. Barreto, C.A. Borda, M.T. Torres, J.C. Gaeta, J.L.S. D. Silva, S.Z.R. Saraiva, I.S.O. Salazar, I.H.A. Cintra, Towards the rebuilding of spiny lobster stocks in brazil: a review, Crustaceana 93 (2020) 957–983, https://doi.org/10.1163/15685403-bja10073.

[95] G.H. Pereira-Filho, G.M. Amado-Filho, S.M.P.B. Guimarães, R.L. Moura, P.Y. G. Sumida, D.P. Abrantes, R.G. Bahia, A.Z. Güth, R.R. Jorge, R.B.F. Filho, Reef fish and benthic assemblages of the trindade and Martin Vaz island group, SouthWestern Atlantic, Braz. J. Oceanogr. 59 (2011) 201–212, https://doi.org/10.1590/s1679-87592011000300001.

[96] M.A.O. Figueiredo, K. Santos de Menezes, E.M. Costa-Paiva, P.C. Paiva, C.R. R. Ventura, Experimental evaluation of rhodoliths as living substrata for infauna at the Abrolhos Bank, Brazil, Cienc. Mar. 33 (2007) 427–440, https://doi.org/10.7773/cm.v33i4.1221.

[97] R.A. Magris, M.D.P. Costa, C.E.L. Ferreira, C.C. Vilar, J.C. Joyeux, J.C. Creed, M. S. Copertino, P.A. Horta, P.Y.G. Sumida, R.B. Francini-Filho, S.R. Floeter, A blueprint for securing Brazil's marine biodiversity and supporting the achievement of global conservation goals, Divers. Distrib. 27 (2020) 198–215, https://doi.org/10.1111/ddi.13183.

[98] Md.O. Soares, T.C.L. Tavares, P.Bd.M. Carneiro, Mesophotic ecosystems: distribution, impacts and conservation in the South Atlantic, Divers. Distrib. 25 (2019) 255–268, https://doi.org/10.1111/ddi.12846.

[99] M.H. Graham, B.P. Kinlan, L.D. Druehl, L.E. Garske, S. Banks, Deep-water kelp refugia as potential hotspots of tropical marine diversity and productivity, Proc. Natl. Acad. Sci. U. S. A. 104 (2007) 16576–16580, https://doi.org/10.1073/pnas.0704778104.

[100] A.B. Anderson, J. Assis, M.B. Batista, E.A. Serrão, H.C. Guabiroba, S.D.T. Delfino, H.T. Pinheiro, C.R. Pimentel, L.E.O. Gomes, C.C. Vilar, A.F. Bernardino, P. Horta, R.D. Ghisolfi, J.C. Joyeux, Global warming assessment suggests the endemic Brazilian kelp beds to be an endangered ecosystem, Mar. Environ. Res. 168 (2021), https://doi.org/10.1016/j.marenvres.2021.105307.

[101] R. Rayfuse, Crossing the Sectoral Divide: Modern Environmental Law Tools for Addressing Conflicting Uses on the Seabed, in: Law Seabed, Banet, Catherine, 2020: pp. 527–552. 〈https://doi.org/10.1163/9789004391567_024〉.

[102] A. Vinhoza, R. Schaeffer, Brazil's offshore wind energy potential assessment based on a Spatial Multi-Criteria Decision Analysis, Renew. Sustain. Energy Rev. 146 (2021), 111185, https://doi.org/10.1016/j.rser.2021.111185.

[103] L.C. Gerhardinger, M. Quesada-Silva, L.R. Gonçalves, A. Turra, Unveiling the genesis of a marine spatial planning arena in Brazil, Ocean Coast. Manag. 179 (2019), 104825, https://doi.org/10.1016/j.ocecoaman.2019.104825.

[104] A. Begossi, P.H. May, P.F. Lopes, L.E.C. Oliveira, V. da Vinha, R.A.M. Silvano, Compensation for environmental services from artisanal fisheries in SE Brazil: Policy and technical strategies, Ecol. Econ. 71 (2011) 25–32, https://doi.org/10.1016/j.ecolecon.2011.09.008.

[105] D.C. Kalikoski, S. Jentoft, P. McConney, S. Siar, Empowering small-scale fishers to eradicate rural poverty, Marit. Stud. 18 (2019) 121–125, https://doi.org/10.1007/s40152-018-0112-x.

[106] K.A. Miller, K.F. Thompson, P. Johnston, D. Santillo, An overview of seabed mining including the current state of development, environmental impacts, and knowledge gaps, Front. Mar. Sci. 4 (2018), https://doi.org/10.3389/fmars.2017.00418.

[107] K.A. Miller, K. Brigden, D. Santillo, D. Currie, P. Johnston, K.F. Thompson, Challenging the need for deep seabed mining from the perspective of metal demand, biodiversity, ecosystems services, and benefit sharing, Front. Mar. Sci. 8 (2021), https://doi.org/10.3389/fmars.2021.706161.

[108] Midas Project, Implications of Midas results for policy makers: recommendations for future regulations, 2016.

[109] R. Kenchington, P. Hutchings, Science, biodiversity and Australian management of marine ecosystems, Ocean Coast. Manag. 69 (2012) 194–199, https://doi.org/10.1016/j.ocecoaman.2012.08.009.

[110] M.M.A. Ministério do Meio Ambiente. Áreas Prioritárias para conservação. 〈http://areasprioritarias.mma.gov.br/2-atualizacao-das-areas-prioritarias〉 (accessed March 1, 2021).

[111] N.C. Ban, T.E. Davies, S.E. Aguilera, C. Brooks, M. Cox, G. Epstein, L.S. Evans, S. M. Maxwell, M. Nenadovic, Social and ecological effectiveness of large marine protected areas, Glob. Environ. Chang. 43 (2017) 82–91, https://doi.org/10.1016/j.gloenvcha.2017.01.003.

[112] T.D. White, A.B. Carlisle, D.A. Kroodsma, B.A. Block, R. Casagrandi, G.A. De Leo, M. Gatto, F. Micheli, D.J. McCauley, Assessing the effectiveness of a large marine protected area for reef shark conservation, Biol. Conserv. 207 (2017) 64–71, https://doi.org/10.1016/j.biocon.2017.01.009.

[113] R. Costanza, R. de Groot, P. Sutton, S. van der Ploeg, S.J. Anderson, I. Kubiszewski, S. Farber, R.K. Turner, Changes in the global value of ecosystem services, Glob. Environ. Chang. 26 (2014) 152–158, https://doi.org/10.1016/j.gloenvcha.2014.04.002.

[114] IBAMA (Brazilian Institute of the Environment and Renewable Resources). Fishing Statistics. Major Regions and Federation Units. Brasília. 2007.

[115] S.F. Teixeira, B.P. Ferreira, I.P. Padovan, Aspects of fishing and reproduction of the black grouper *Mycteroperca bonaci* (Poey, 1860) (Serranidae: Epinephelinae) in the Northeastern Brazil, Neotrop. Ichthyol. 2 (2004) 19–30.