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AMEAÇAS DA MINERAÇÃO DE CARBONAROS MARINHOS E DA ENERGIA EÓLICA "OFFSHORE" NA BIODIVERSIDADE MARINHA: UM PONTO CRÍTICO PARA A ECONOMIA AZUL

FORTALEZA

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Tese de Doutorado apresentada ao Programa de Pós-Graduação em Ciências Marinhas Tropicais, da Universidade Federal do Ceará, como requisito parcial para obtenção do Título de Doutora em Ciências Marinhas Tropicais. Área de Concentração: Ciência, tecnologia e Gestão Costeira e Oceânica.

Orientador: Prof. Dr. Marcelo de Oliveira Soares
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Aos meus pais, Vera Lúcia e José Lima.
Aos meus avós Maria do Carmo, Raimundo Vieira, Maria Adelia, Raimundo Paiva.

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“Tempo rei, ó, tempo rei, ó, tempo rei
Transformai as velhas formas do viver
Ensinai-me, ó, pai, o que eu ainda não sei
Mãe Senhora do Perpétuo, socorrei (...)”

Gilberto Gil

RESUMO

Os ecossistemas marinhos são fundamentais para a manutenção da vida no planeta, proporcionando inúmeros benefícios diretos e indiretos. Nesse contexto, a partir da necessidade do uso sustentável dos oceanos e da expansão econômica, surgiu o conceito de Economia Azul, que assegura o uso rentável e sustentável dos recursos providos pelo mar. Nesse contexto, a presente tese foi organizada em dois capítulos na forma de artigos científicos internacionais a respeito de duas atividades emergentes no ambiente marinho e que podem impactar diretamente no uso sustentável dos oceanos. O primeiro capítulo tratou da mineração dos carbonatos marinhos no Atlântico Sudoeste Ocidental, seu atual status, potenciais impactos e ações de conservação. Os carbonatos marinhos têm importância econômica devido a sua alta concentração de cálcio, sendo abundantes em algas calcárias, principalmente na forma de rodolitos. O Brasil possui grandes depósitos de carbonatos marinhos estimados em 2.10^{11} toneladas, com potencial de exploração de 96.000 a 120.000 t/ano, o que desperta interesse da indústria global e nacional. No entanto, o crescente interesse na mineração está ameaçando ecossistemas únicos, como os bancos de rodolitos, pois muitos processos ativos de mineração estão nessas áreas. Atualmente, não há informações científicas suficientes para fundamentar a exploração segura desses recursos, além dos possíveis impactos na conectividade com outros ambientes como recifes de corais. Então para que essa atividade seja melhor estabelecida, são necessárias ações de política ambiental que priorizem a saúde dos bancos de rodolitos, como o planejamento espacial marinho. O segundo capítulo tratou das ameaças da instalação de Parques eólicos offshore aos sistemas recifais tropicais. Esses empreendimentos também despontam no cenário da economia azul mundial por se tratar de geração de energia renovável. Os parques consistem na instalação de aerogeradores no mar, que apresentam vantagens devido às altas velocidades do vento e a possibilidade de altas taxas de ocupação do solo. Atualmente, no Brasil estão previstas a instalação de 66 parques eólicos, com o total de 3.364 aerogeradores intalados no mar e potencial de produção de 48.410 MW (até novembro de 2022). Desses, 18 parques estão em processo de licenciamento na costa semiárida do Atlântico Sudoeste equatorial. Embora seja uma fonte de energia limpa, esses parques podem afetar de diferentes maneiras os sistemas recifais, como destruição de habitat, soterramento, favorecimento da dispersão de espécies invasoras, como o coral-sol e o peixe-leão, etc. Através da sobreposição de dados espaciais, detectamos, de modo inédito, que 83.3% dos projetos de parques eólicos (15 empreendimentos) estão previstos para serem instalados em áreas de alta importância biológica, como sistemas recifais. Muitos dos projetos também estão localizados a menos de 20 km de distância de áreas de ocorrência de espécies invasoras. Os resultados de ambos artigos ressaltam a necessidade de políticas urgentes de ação de conservação para a preservação desses ecossistemas marinhos de alta importância biológica, como estudos de impactos ambiental baseados em evidências científicas, planejamento espacial marinho adequado, criação de novas áreas marinhas protegidas no-take e outras políticas de conservação, de modo a fornecer subsídios para discutir caminhos para a economia azul no Atlântico Sul.

PALAVRAS-CHAVE: Rodolitos, Carbonato de cálcio, Serviços ecossistêmicos, Energias renováveis, Sustentabilidade, Recifes

ABSTRACT

Marine ecosystems are essential for sustaining life on the planet, that provide numerous direct and indirect benefits. In this context, from the need for sustainable use of the oceans, and the planned expansion of activities in various marine sectors, the concept of Blue Economy emerged, which ensures the profitable and sustainable use of the resources provided by the sea. In this context, this thesis was organized into two chapters in the form of international scientific articles about two emerging activities in the marine environment that can directly impact the sustainable use of the oceans. The first chapter dealt with the mining of marine carbonates in the Western Southwest Atlantic, its current status, potential impacts and conservation actions. Marine carbonates are economically important due to their high concentration of calcium, being abundant in calcareous algae, mainly in the form of rhodoliths. Brazil has large deposits of marine carbonates, estimated at $2{,}10^{11}$ tons, with an exploration potential of 96,000 to 120,000 t/year. However, the growing interest in mining is threatening unique ecosystems such as rhodolith beds, as many active mining processes are in these areas. Currently, there is not enough scientific information to support the safe exploitation of these resources, in addition to the possible impacts on connectivity with other environments such as coral reefs. So for this activity to be better established, environmental policy actions are needed that prioritize the health of rhodolith banks. The second chapter dealt with the threats posed by the installation of offshore wind farms to tropical reef systems. These projects are also emerging in the scenario of the world's blue economy because they are renewable energy generation. The parks consist of the installation of wind turbines at sea, which have advantages due to high wind speeds and the possibility of high rates of land occupation. Currently, in Brazil, the installation of 66 wind farms is planned, with a total of 3,364 wind turbines installed at sea and a production potential of 48,410 MW (until November 2022). Of these, 18 parks are in the licensing process on the semi-arid coast of the equatorial Southwest Atlantic. Although it is a source of clean energy, these parks can affect reef systems in different ways, such as habitat destruction, burial, favoring the dispersal of invasive species such as sun coral and lionfish, etc. By overlaying spatial data, we detected, in an unprecedented way, that 83.3% of wind farm projects (15 enterprise) are expected to be installed in areas of high biological importance, such as reef systems. Many of the projects are also located less than 20 km away from areas where invasive species occur. The results of both articles highlight the need for urgent conservation action policies for the preservation of these marine ecosystems of high biological importance, such as studies of environmental impacts based on scientific evidence, adequate marine spatial planning, creation of new no-take marine protected areas and other conservation policies, in order to provide subsidies to discuss paths towards a blue economy in the South Atlantic.

Keywords: Rhodoliths, Calcium carbonate, Ecosystem services, renewable energy, sustainability

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1. INTRODUÇÃO GERAL

Os oceanos desempenham um papel fundamental para a humanidade e o planeta no âmbito ambiental, cultural, social e econômico. Os ecossistemas marinhos são um dos mais explorados e as intensas atividades humanas vem ameaçando severamente esses ambientes e os serviços que eles promovem (LAU 2013), principalmente desde a segunda metade do século XX e mais rapidamente que em qualquer outro momento da história da humanidade (MEA 2005). É esperado que as atividades econômicas desempenhadas no mar (transporte marítimo; recursos energéticos e minerais; pesca e aquicultura; turismo, etc) cresçam substancialmente nos próximos anos e se expandam nos mais diversos setores, criando novas oportunidades econômicas e também muitos impactos socioambientais no contexto do crescimento da Economia do Mar. Entretanto, tais impactos podem afetar os serviços ecossistêmicos marinhos e a saúde dos oceanos.

Os serviços ecossistêmicos são os benefícios diretos e indiretos obtidos pelo homem a partir do funcionamento dos ecossistemas e que apresentam valor econômico real ou potencial, sendo classificados em serviços de (a) **provisão** (que consistem de alimentação, uso de material biológico como fonte de energia, recursos genético e farmacológicos e etc); (b) **serviços de regulação** (incluem regulação da qualidade do ar, regulação climática, purificação da água e tratamento de resíduos, regulação de pestes, polinização); (c) **serviços culturais** (aqueles que trazem benefícios não materiais, como enriquecimento espiritual, desenvolvimento cognitivo, recreação, conhecimentos tradicionais, valores educacionais ou de pertencimento, e etc); e (d) **serviços de suporte** (que são aqueles dos quais os demais serviços ecossistêmicos dependem, são exemplos deles a formação do solo, a fotossíntese, a produção primária, ciclagem de nutrientes e da água, e etc) (ARMOŠKAITĖ *et al*., 2020; COSTANZA *et al*., 1997, 2014; MEA 2005).

A diminuição da complexidade dos habitats marinhos e desses serviços se deve aos inúmeros estressores no ambiente marinho que estão relacionados ao desenvolvimento humano como a sobrepesca, acidificação dos oceanos, poluição, mudanças climáticas, aumento de turbidez, dentre outros (BAN; GRAHAM; CONNOLLY, 2014; HUGHES *et al.*, 2018). A partir da necessidade da utilização sustentável dos recursos marinhos gerou o conceito de **Economia Azul**, que incorpora os serviços ecossistêmicos prestados pelos oceanos na economia, mas de modo sustentável, garantindo que as atividades sejam rentáveis, mas que continuem provendo os serviços ecossistêmicos de modo saudável (MULAZZANI; MALORGIO, 2017). Ou seja, o crescimento econômico deve ser compatível com a saúde dos ecossistemas marinhos (LILLEBØ *et al.*, 2017), integrando os serviços prestados pelos oceanos e o uso humano de modo holístico. O conceito da economia azul surge para modificar o conceito pretérito de Economia do Mar e a urgente necessidade de integrar a sustentabilidade e a conservação no manejo das atividades marinhas, de modo a promover a manutenção da biodiversidade e dos serviços ecossistêmicos marinhos nos próximos anos.

As Nações Unidas proclamaram o período de 2021 a 2030 como a Década da Ciência do Oceano para o Desenvolvimento Sustentável para combinar os esforços mundiais de todos os setores com o objetivo de reverter o ciclo indesejável de declínio da saúde dos oceanos (UNESCO, 2022). Por isso, harmonizar a relação entre a saúde do ambiente marinho e a pressão humana exercida sobre o mesmo deve ser uma ação prioritária. Mais recentemente, a 2ª Conferência Global dos Oceanos (2022) realizada em Lisboa, Portugal, elaborou uma declaração intitulada “O nosso oceano, o nosso futuro, a nossa responsabilidade”, nela é reafirmada a necessidade de desenvolver e implementar medidas para mitigar os impactos das mudanças climáticas, como o uso de tecnologias de energias renováveis (UN, 2022). Os oceanos são um ambiente fluido, complexo, de usos múltiplos, interconectado e a sua compartimentação em setores (ex. ambientes costeiros, mar profundo) na prática não funciona, então trabalhar os impactos de maneira isolada acaba sendo um desafio (SMITH-GODFREY, 2016). Nesse contexto, o planejamento espacial marinho é uma ferramenta de política pública, estratégica e participativa, para o ordenamento dos diversos usos no espaço marinho, afim de reduzir diversos conflitos e garantir a integridade dos ambientes e manutenção dos serviços ecossistêmicos (Ehler & Douvere, 2009). Dessa forma, é importante aplicar um Planejamento Espacial Marinho factual, visando promover o equilíbrio entre as atividades de valor econômico e a manutenção dos bens e serviços ecossistêmicos.

O report “*The Blue Economy: Growth, Opportunity and a Sustainable Ocean Economy*”, publicado pela The Economist Intelligence Unit 2015, considera a economia azul como uma economia sustentável para os oceanos, que surge quando a atividade econômica está em equilíbrio com a capacidade dos ecossistemas oceânicos de suportarem as atividades e permanecerem saudáveis a longo prazo (GODDARD, 2015; SMITH-GODFREY, 2016). Na Rio +20, a economia azul foi proposta com uma forma de melhorar o bem-estar humano e trazer equidade social, mas reduzindo os riscos ambientais e o uso eficiente dos recursos (SMITH-GODFREY, 2016; UNITED NATIONS CONFERENCE ON SUSTAINABLE DEVELOPMENT, 2012). De modo semelhante, o documento "*Complexity in small Island Developing States* também define a economia azul como uma atividade ligada ao bem-estar humano, equidade social e redução dos riscos ambientais (EVEREST-PHILLIPS, 2014). Em resumo, a economia azul enfatiza o uso dos recursos marinhos de forma sustentável, equidade social e o benefício de todos, havendo balanço entre as atividades econômicas, o suporte às comunidades diretamente afetadas e a manutenção dos sistemas ecológicos. Nesse contexto, duas atividades econômicas mundiais em ascensão (mineração de carbonatos e energias eólicas offshore) necessitam de uma profunda discussão multisetorial face aos seus possíveis impactos e a sua insustentabilidade ou sustentabilidade. Nesses temas, a presente tese de doutorado pretende avançar de modo inédito.

1.1. Mineração de carbonatos marinhos

Os limites para a exploração e obtenção de recursos avançam cada vez mais para o ambiente marinho, que se revela como um reservatório de minerais a serem explorados economicamente. A mineração marinha tem se mostrado cada vez mais viável economicamente, principalmente com o advento de novas tecnologias de detecção e exploração do fundo marinho de baixo custo (WEDDING *et al.*, 2015). Contudo, o grande desafio é permitir a exploração de modo que a sustentabilidade seja garantida, já que os fundos oceânicos são ambientes frágeis e com baixo conhecimento científico, havendo risco para a biodiversidade (WEDDING *et al.*, 2015). Consequentemente, existe um risco para a integridade dos bens e serviços ecossistêmicos prestados pelos oceanos, o que compromete a possível existência de uma Economia Azul.

Dentre os recursos que podem ser minerados dos bancos ou fundos marinhos, estão os carbonatos marinhos, que são formados por areias e cascalhos de origem biogênica, como algas calcárias, nódulos de rodolitos, corais, fragmentos de conchas de moluscos, foraminíferos, briozoários bentônicos, dentre outros (DIAS, 2000; PINHEIRO *et al.*, 2020). Os carbonatos marinhos, principalmente na forma de algas calcárias, vem sendo historicamente exploradas para fins industriais na Europa e outras regiões, principalmente para a indústria agropecuária, por se tratarem de importante fonte de nutrientes, sendo caracterizados como fertilizantes ricos em carbonatos de cálcio e magnésio, além de diversos oligoelementos, como Fe, Mn, B, Ni, Cu, Zn, Mo, Se, Sr (DIAS., 2000; MOREIRA et al. 2011).

A exploração dos carbonatos é antiga e conhecida desde antes do século 18, sendo uma atividade muito importante para a construção da civilização européia antiga (COLETTI; BASSO; FRIXA, 2017). Atualmente, a França contém o maior depósito de *Maerl* (um tipo de alga coralínea vermelha) do mundo, concentrado na região da Britânia (AUGRIS; BERTHOU, 1990; GRALL, J.; HALL-SPENCER, J. M., 2003), cuja exploração foi feita de maneira insustentável (HALL-SPENCER *et al.*, 2000), promovendo severas alterações na biodiversidade dos organismos bentônicos (BIOMAERL TEAM, 1999; CABIOCH, 1969). Este exemplo deve ser observado pelo Brasil, pois a França baniu a extração deste recurso em 2011 e parte do Reino Unido também adotou medida semelhante (HALL-SPENCER, 2005), reduzindo a pressão nos bancos, de modo a tentar recuperar a biodiversidade desses locais bem como a provisão de serviços ecossistêmicos.

A plataforma continental do Brasil possui um dos mais extensos depósitos de carbonatos marinhos do mundo, inclusive na forma de bancos de rodolitos (DIAS, 2000), representando, desta forma, o maior depósito de carbonato de cálcio no Atlântico oeste tropical (AMADO-FILHO *et al.*, 2012). Os rodolitos são algas calcárias de vida livre na forma de nódulos, compostas parcialmente ou completamente por algas vermelhas calcárias não geniculadas (Corallinophycidae, Rhodophyta), impregnam carbonato de cálcio em suas paredes celulares e possuem crescimento lento, em torno de 1 a 1,5mm/ano (AMADO-FILHO et al. 2012). Os rodolitos são considerados habitats para muitas espécies (BROOM *et al.*, 2008; FOSTER *et al.*, 2007; HALFAR; RIEGL, 2013; RIOSMENA-RODRÍGUEZ, 2017), por construírem um complexo tridimensional (BASSO *et al.*, 2016; FOSTER *et al.*, 2013; GRALL; GLÉMAREC, 1997), provendo inúmeros serviços ecossistêmicos como áreas de berçário, além de estocar carbono (HEIJDEN, 2015; HORTA; AMADO-FILHO; GURGEL, 2016; MOURA *et al.*, 2021). No Nordeste do Brasil, os ambientes de rodolitos funcionam como áreas de berçário e forrageamento da lagosta *Panulirus* spp., um importante recurso econômico do setor de pesca e pesca artesanal para essa região (COUTINHO; MORAIS, 1970; FONTELES-FILHO, 2008; FAUSTO-FILHO, 1969).

Em virtude de sua extensão, os rodolitos no Brasil estão sobre forte pressão por (1) possuírem imenso potencial econômico (AMADO-FILHO *et al.*, 2012; AMADO-FILHO; PEREIRA-FILHO, 2012; MARINS *et al.*, 2012; TESTA; BOSENCE, 1999), (2) pelo advento de novas tecnologias para a exploração dos ambientes rasos e mesofóticos (0 – 150 m) e (3) pela escassez dos recursos terrestres (WEDDING *et al.*, 2015). No Brasil, os rodolitos se configuram como o principal recurso mineral a ser potencialmente explorado nas águas rasas, porém é imprescindível compreender como se configuram os bancos presentes ao longo da costa brasileira, seus habitats, tamanho e estrutura, a diversidade associada, bem como os bens e serviços ecossistêmicos oferecidos. Nesse contexto, pesquisas nesse tema são escassas e serão alvo desta tese no capítulo 1 pelo seu ineditismo e potencial de aplicação prática para a tomada de decisões políticas com base em conhecimento científico.

1.2. Energia eólica *offshore*

Um outro tema igualmente relevante e pouco discutido no âmbito da Economia Azul são as energias renováveis marinhas, em especial a instalação e operação de parques eólicos *offshore* na plataforma continental tropical. As fontes de energia limpa, como a energia gerada pelos ventos, maré e solar vem ganhando destaque por constituírem uma fonte de energia pouco poluidora e sustentável, em crescente adesão por países como Reino Unido, China e Alemanha (KOTHARI; TYAGI; PATHAK, 2010; KABIR et al. 2018; CHOWDHURY et al. 2021). A energia eólica vem ganhando destaque por se tratar de uma importante alternativa para ao alcance das metas de diminuição da emissão de gases de efeito estufa, e, no caso das eólicas *offshore*, é uma diversificação das fontes da matriz elétrica renovável, ganhando cada vez mais destaque no cenário nacional e internacional (DECASTRO *et al.*, 2019; EPE, 2020).

A produção de energiapelos parques eólicos *offshore* pode ser convertida em combustível limpo na forma de hidrogênio verde. O hidrogênio verde é produzido a partir de fontes renováveis de energia, como dos ventos, solar, nuclear, energia das marés e etc (LI, 2017), sendo a energia solar e a eólica as mais comuns até o presente momento (D'AMORE-DOMENECH, LEO, 2019). Como as energias renováveis dependem de condições climáticas e consequentemente das instabilidades ambientais, o armazenamento por meio da produção de hidrogênio é um forte aliado às energias limpas, pois ele retém grandes quantidades dessa energia renovável produzida, podendo ser transportada, possibilitando assim o comércio desse hidrogênio e exportado (GANIYUA; MARTÍNEZ-HUITLEA; RODRIGO, 2020; ALMUTAIRI ET AL, 2021). Nesse contexto, pode configurar uma importante via alternativa do uso de combustíveis fósseis e descarbonização da matriz energética (MIRANDA, 2018).

Os parques eólicos *offshore* consistem na implementação de aerogeradores no mar, que transformam a energia cinética do vento em energia mecânica a partir do giro das pás, com a consequente geração de energia elétrica. A instalação de parques eólicos *offshore* apresentam vantagem em relação aos parques *onshore*, já que não há barreiras físicas no mar, há baixa rugosidade da superfície, altas velocidades do vento e a possibilidade de altas taxas de ocupação do solo marinho (EPE, 2020) devido a vastidão das zonas econômica-exclusiva das nações. Contudo, é necessário que essas estruturas sejam projetadas de modo a estarem protegidas contra corrosão, ação de ondas e marés, e haja uma infraestrutura de logistica para construção, manutenção e funcionamento das mesmas (EPE, 2020).

Há muitos projetos de parques eólicos offshore espalhados pelo mundo, havendo destaque para o Reino Unido, Alemanha e China, que do total de parques eólicos instalados até 2019, concentram mais de 90% dos 23,1 GW instalados de energia elétrica (EPE, 2020; GWEC, 2019), sendo essas instaladas em plataformas continentais de clima temperado. A Europa se destaca nesse mercado de geração de energia, tanto em aerogeradores instalados quanto em novas instalações (EPE, 2020). No mercado asiático, além da China, outros países como Japão, Taiwan, Coréia do Sul, Vietnã e Índia vem apontando nesse mercado também (EPE, 2020; NREL, 2017). Os EUA iniciaram, em 2016, suas atividades na indústria de eólicas *offshore* com o lançamento do projeto *Deepwater Wind* de 30 MW (NREL, 2017).

Como parte de estratégias para desenvolver a indústria *offshore* sustentável e robusta, o Brasil lançou, também em 2016, a Estratégia Nacional de Energia Eólica *Offshore* de modo a identificar as principais ações para atingir a meta de 86 GW a ser implantada até 2050. Atualmente, o Brasil não possui parques eólicos *offshore* em operação comercial, mas, no ambiente terrestre, esta atividade se encontra em plena expansão e já conta com uma vasta experiência acerca dessas instalações *onshore* (BRANNSTROM *et al.*, 2017). Até o momento, 66 projetos de parques eólicos *offshore* estão em processo de licenciamento ambiental junto ao IBAMA (governo federal), nos estados do Maranhão (1), Ceará (18), Piauí (4), Rio Grande do Norte (8), Espírito Santo (4), Rio de Janeiro (9), Rio Grande do Sul (21) e Santa Catarina (1) (IBAMA, 2022). A maioria dos projetos contempla a região Nordeste do país (IBAMA, 2022), o qual é um ambiente tipicamente tropical e com velocidades médias anuais dos ventros acima de 6.4m/s (ADECE, 2022).

Os parques eólicos offshore são implementados no mar territorial[1] ou na zona economicamente exclusiva[2] (BRASIL, 1993), que são áreas da União. Nesse contexto, a instalação de parques eólicos *offshore* demanda que a área requerida seja definida como área a ser concedida para a iniciativa privada, já que outros empreendedores são excluídos do processo. Nos termos da lei n. 9636/1998, esse processo é legal, já que imóveis da união podem ser cedidos para pessoas físicas ou jurídicas quando há interesse econômico de uso nacional (BRASIL, 1998). Em relação às instalações das eólicas *offshore*, como outras instalações feita pelo homem no mar, é fundamental que haja o planejamento espacial marinho de modo a criar um manejo e uso sustentável pelos múltiplos atores e ainda assim haver promoção da conservação e da Economia Azul. É importante, aqui, destacar os usos múltiplos do espaço oceânico, como pesca, aquicultura, navegação, recreação, mineração, turismo, extração de petróleo e gás, zonas de interesse arqueológico, dentre outros (EPE, 2020; HAMMAR; PERRY; GULLSTRÖM, 2016). Entretanto, o Brasil não possui e caminha lentamente para a implantação de um Planejamento Espacial Marinho; documento que se bem elaborado e implementado do ponto de vista científica, pode ajudar no uso dos oceanos por diversos setores de forma sustentável.

A energia eólica offshore pode gerar diversos impactos que podem afetar o ambiente marinho nos componentes biótico, físico e socioeconômico. Efeitos negativos, como mudanças comportamentais, desorientação e morte de animais, podem ser observados em mamíferos marinhos, tartarugas e peixes em geral, devido ao ruído excessivo dos parques eólicos promovidos desde a fase de implantação, passando pela fase de operação (a menos ruidosa) até o descomissionamento (EPE, 2020; HAMMAR; PERRY; GULLSTRÖM, 2016; MADSEN *et al.*, 2006; TOUGAARD *et al.*, 2009). Esses ruídos excessivos podem ser decorrentes do movimento “bate estaca” de fixação das bases estruturantes dos aerogeradores, do funcionamento das turbinas, da instalação dos cabos submarinos, bem como da fase de descomissionamento que se dá através de explosivos (EPE, 2020; HAMMAR; PERRY; GULLSTRÖM, 2016). Dos impactos negativos a respeito da megafauna, ainda é possível ressaltar os danos às aves migratórias, que colidem nas

[1] Segundo a lei brasileira n. 8617/1993, esta área corresponde a faixa de 12 milhas marítimas de largura, medidas a partir da linha de baixa-mar do litoral continental e insular.
[2] Segundo a lei n. 8617/1993, esta área compreende a faixa que se estende das doze às duzentas milhas marítimas.

hélices das turbinas, ou mesmo mudam sua rota de migração devidos aos obstáculos encontrados (DESHOLM; KAHLERT, 2005; GRECIAN *et al.*, 2010).

Os parques eólicos *offshore* geralmente são instalados em substrato inconsolidado, podendo ser lama, areia, cascalho, ou mais raramente em substratos duros (HAMMAR; ANDERSSON; ROSENBERG, 2010) devido a maioria desses empreendimentos terem sido instalados em plataformas continentais de países de clima temperado, onde a sedimentação carbonática é reduzida. Os impactos das instalações dessas estruturas em ambientes rochosos ainda se tratam de especulações e ainda são pouco estudados (SCHLÄPPY; ŠAŠKOV; DAHLGREN, 2014; SHIELDS *et al.*, 2009). Os impactos dessas instalações não são conhecidos para todos os táxons e ecossistemas, contudo, é sabido que as comunidades bentônicas localizadas em ambientes pristinos ou prioritários para conservação, são mais vulneráveis aos impactos. Ambientes costeiros também podem sofrer drasticos danos devido a eventos como as ondas geradas pelo tráfego de embarcações de apoio, derramamento de óleo, dragagem, a instalação dos cabos e estruturas onshore e offshore associadas, ressuspensão de sedimento, alteração da qualidade da água e aumento da turbidez, desestabilização do subsolo marinho, gerando assim fragmentação de habitats, alterações hidrológicas, perda de barreiras importantes para os ambientes marinhos e costeiros (EPE, 2020). Desse modo, é claro que se medidas mitigatórias não forem adotadas e o local de instalação das torres não for bem planejado, poderão haver muitos danos.

Por outro lado, os parques eólicos podem atuar direta ou indiretamente na conservação, já que o substrato duro das estruturas artificiais das torres atrai espécies e pode contribuir no enriquecimento da fauna local (LANGHAMER, 2012), atuando como um recife artificial em ambientes inconsolidados. Experiências em outros países mostram que esses ambientes podem favorecer o desenvolvimento de comunidades de peixes, pois é criado um ambiente abrigado e a pressão de pesca é diminuída (HAMMAR; PERRY; GULLSTRÖM, 2016). No entanto, um grande desafio pode surgir em decorrência do novo habitat formado. Espécies invasoras que já impactam o litoral brasileiro, como o coral sol e o peixe leão, podem ser atraídas pela disponibilidade de habitat e alimento (BRAGA *et al.*, 2021; SOARES *et al.*, 2022), ocasionando desafios para o equilíbrio da região tropical do Atlântico Sul.

Embora se apresente como uma fonte de energia limpa e renovável, os parques eólicos apresentam uma série de impactos socioambientais em todo o mundo (SNYDER; KAISER, 2009).

Por isso, é importante que os riscos ambientais sejam identificados, evitados e mitigados desde o início do projeto, passando pela instalação, operação e descomissionamento dos aerogeradores. Dessa forma, o planejamento espacial marinho é de grande importância, já que esses parques possuem características próprias e que podem afetar de diferentes formas os ecossistemas marinhos e os impactos em ambientes rochosos, como os nossos recifes costeiros tropicais, ainda são desconhecidos.

Assim, a partir dos usos múltiplos do ambiente marinho e da necessidade da manutenção dos serviços ecossistêmicos, o ambiente marinho precisa ser organizado de modo a garantir seus usos (SANTOS ET AL. 2019). Para tal, através de um processo integrado com vários setores da sociedade e de dados científicos de qualidade, deve ser cuidadosamente avaliado quais atividades podem afetar ambientes de importância ecológica ou que são conflitantes com outros setores, e a partir disso, ser decidido quais espaços são mais indicados para o desenvolvimento de determinadas atividades (SANTOS ET AL. 2019).

Diante disso, os objetivos dessa tese foram discutir os impactos da mineração de carbonatos e dos parques eólicos offshore nos bancos de rodolitos e nos recifes tropicais da costa semiárida do Nordeste. Em adição, a pergunta que permeou o presente estudo foi se "as atividades da economia azul podem causar danos irreversíveis em ambientes naturais de alta importância biológica?" Para isso, a tese está organizada em dois capítulos com temas inéditos. No primeiro apresentamos uma discussão sobre os impactos da mineração marinha de carbonatos nos inexplorados bancos de rodolitos, os conflitos com a socioeconômicos e os impactos na biodiversidade do Atlântico Sul. Abordamos a hipótese de que a exploração desses carbonatos marinhos nos bancos de rodolitos e sua biodiversidade podem causar impactos irreversíveis. No segundo capítulo, abordamos os impactos da implantação dos parques eólicos *offshore* nos ambientes recifais do litoral semiárido brasileiro, testando a hipótese de que essas estruturas irão impactar áreas naturais de importância para a biodiversidade, a partir da análise de dados disponíveis na literatura e plataformas oficiais do govenro até novembro de 2022. Nos dois capítulos foram feitas análises espaciais usando o software QGIS a partir de bases cartográficas no formato *shapefile* e a partir dos mapas gerados avaliamos os impactos dessas atividades marinhas de modo inédito. Os 2 capítulos estão em língua inglesa visando a publicação em revistas internacionais de alto fator de impacto (> 4,0), devido ao ineditismo de ambos os temas. O primeiro capítulo foi submetido durante a qualificação e publicado na revista Marine Policy e o segundo foi submetido para a revista Nature Sustainability.

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3. OBJETIVOS

3.1. Objetivo Geral

Discutir o impacto na biodiversidade de duas atividades econômicas em ascensão no ambiente marinho (mineração de carbonatos marinhos nos bancos de rodolitos e instalação de eólicas offshore) na costa brasileira, principalmente no Ceará, como subsídio para discutir os caminhos para a Economia Azul no Atlântico Sul.

3.2. Objetivos Específicos

1. Discutir o impacto na extração de carbonatos marinhos nos bancos de rodolitos no litoral brasileiro, e revisar os impactos e conflitos da atividade com outros setores da economia azul;

2. Discutir os impactos da instalação de parques eólicos offshore em áreas de importância biológica na costa semi-árida do Nordeste do Brasil (estado do Ceará) e discutir os impactos na conservação marinha, principalmente no contexto dos objetivos de desenvolvimento sustentável e da agenda 2030.

4. CAPÍTULO 1 - Marine carbonate mining in the Southwestern Atlantic: current status, potential impacts, and conservation actions.

Artigo aceito na revista Marine Policy (Elsevier) – Apêndice

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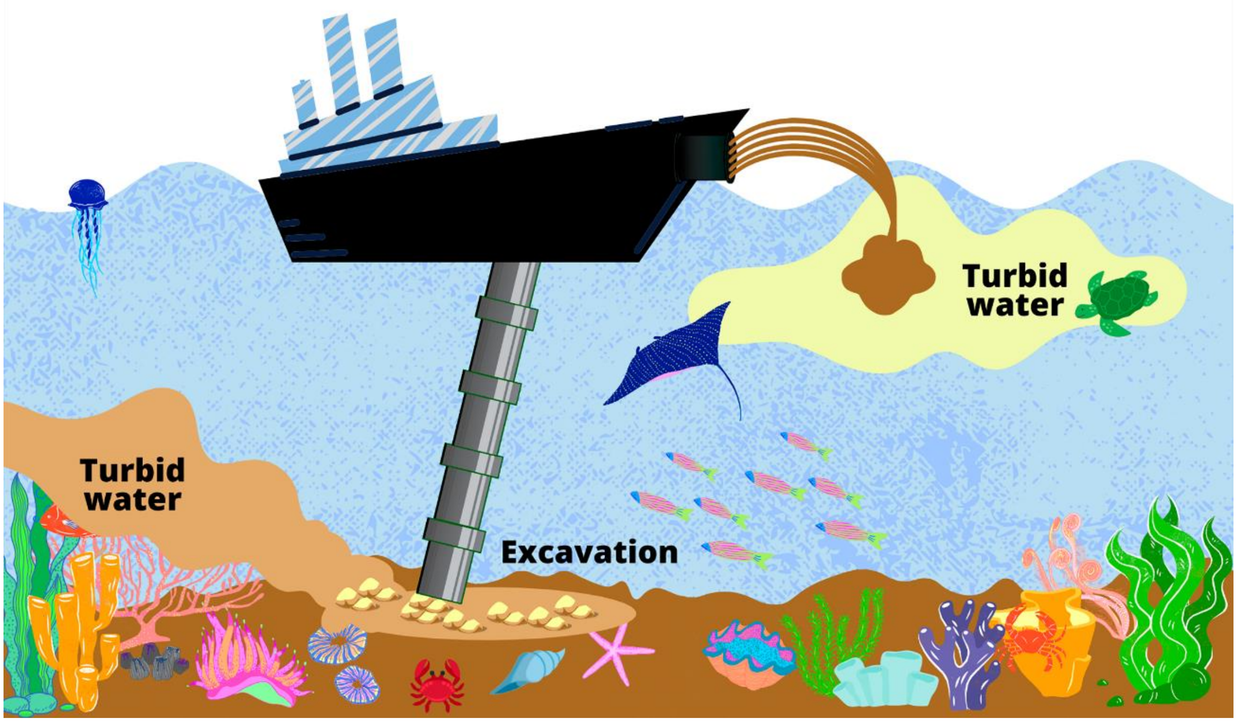
Graphical abstract



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 1,355,157,240 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.

Keywords: Calcareous algae, Marine carbonate sediments, Rhodolith beds, Marine Protected Areas, Brazil

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 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] (Figure 1). Moreover, rhodolith beds provide important ecosystem goods and services, acting as reef nursery areas, fishing grounds, and carbon stocks [18–20].

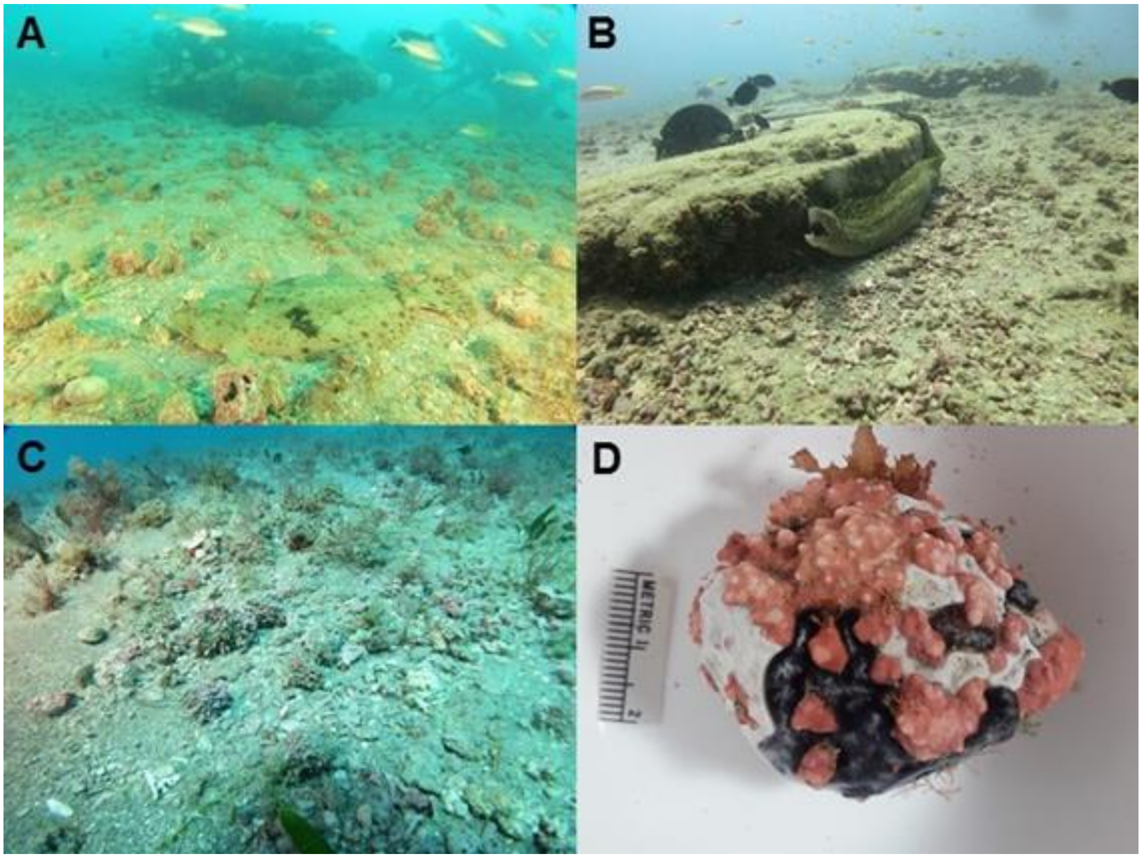


Figure 1 - The biodiversity that is associated with the complex three-dimensional seascape which is structured by rhodolith beds in the South Atlantic Ocean. (A, B) – Demersal fish associated with the rhodolith bottom (*Bothus* sp. and *Acanthurus chirurgus*), (C) - Epilithic macroalgae and seagrasses 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.

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 such as the burial of the organisms or inhibition of photosynthesis due to increased turbidity [29, 33] (Figure 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.

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) [42, 43] over more than 4,000 km. All of these regions have heterogeneous seabeds with the potential for the exploitation of carbonate [44–46]; however, most of these deposits are found in the North and Northeast regions (Figure 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. [47]; Ximenes Neto et al., [48]; Dias et al., [49]; and Morais et al. [50]), 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 [51].

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 [52, 53], 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 [54]. In this context, rhodolith beds play an important role in the provision of ecosystem services and food security [55].

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 [42]. In Zone A (0–15° S; Figure 2) both branching coralline algae and green algae (e.g., *Halimeda* spp.) predominate. In Zone B (15–23° S; Figure 2), *Halimeda* algae are also present but the dominant algae are the reef-builders, coralline algae [56]. 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 [42]. 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 (Figure 2) in this study.

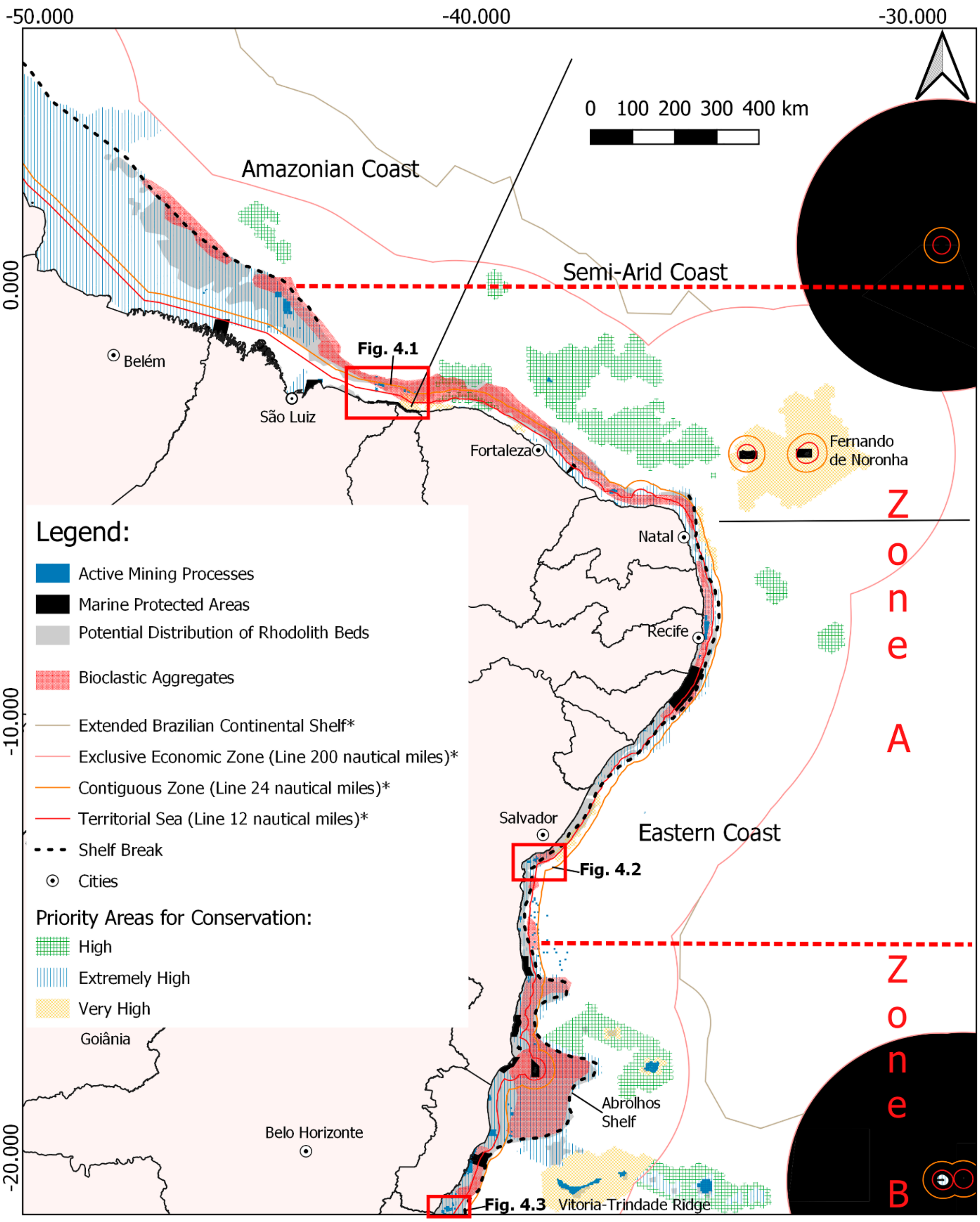


Figure 2 - Active mining processes, carbonate bottoms, and marine biodiversity hotspots along the Brazilian coast: the Amazonian shelf to the Vitoria-Trindade Ridge. This figure highlights active mining processes, marine protected areas, and priority areas for conservation. Zones A and B refer to the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

The northernmost region, Zone A (Figure 2), especially in the equatorial portion [57], has the largest coverage in the extent of known carbonate sediments since the 1960s, consisting mainly of coralline and *Halimeda* algae, with a smaller contribution from mollusks, bryozoans, and foraminifera [43, 45]. 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, 58] but are interconnected to the southernmost portion of the Amazon reefs [59], one of the largest and understudied mesophotic ecosystems in the South Atlantic.

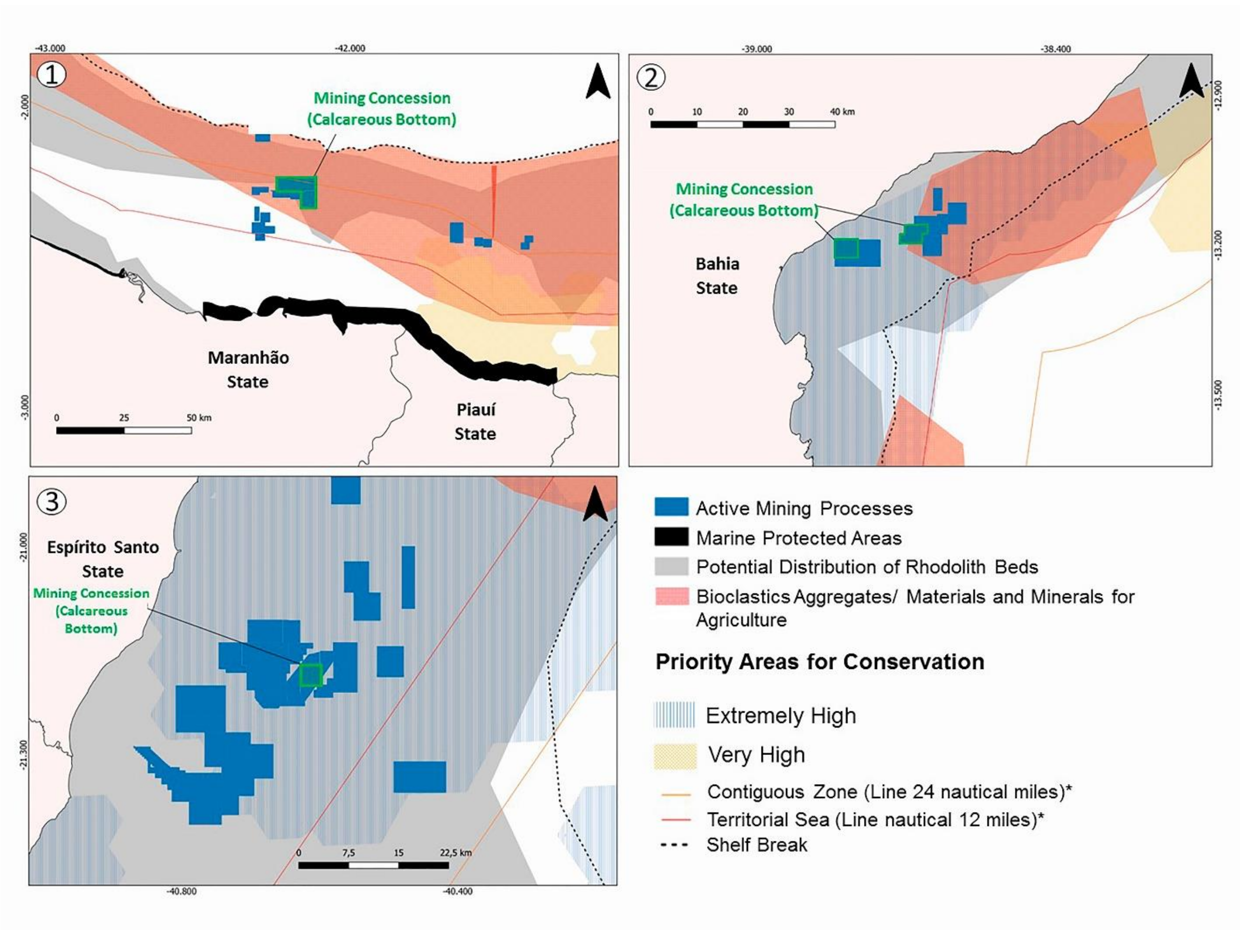


Figure 3 - The active process highlighting the mining concessions that overlap or are close to the rhodolith beds, marine protected areas, and priority areas for the conservation of the tropical marine biodiversity (South Atlantic, Brazil). (3.1) Maranhão and Piauí coast; (3.2) Bahia coast; and (3.3)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

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 (Figure 2), where there is a predominance of *Halimeda* sand or gravel, followed by coralline algae, mollusks, and bryozoans [8, 50]. This area 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 [8,47,60]. The second area is the west coast, where coralline algae fragments and rhodolith nodules predominate, with the secondary accumulation of other organisms [8, 60]. Therefore, from Maranhão State to Fortaleza City (Ceará State; Figure 2), there is a large concentration of coralline algae and nearshore rhodolith beds in the shallow continental shelf [60, 61], 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 (Figures 2 and 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 subtropical zone; Figure 3.3) also has extensive rhodolith beds, especially in the Vitória-Trindade Chain, which is rich in coralline algae [62]. Brazilian $CaCO_3$ deposits are estimated to be the largest worldwide [45, 63], with a total of 2×10^{11} tons and a current lower estimate of extraction at 96,000–120,000 tons per year [64]. 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 1,355,157,240 tons of $CaCO_3$.

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 Figures 3 and 4 for the geographical locations). Source: Cavalcanti (2020) [8].

Mineral reserves (t)				
Bahia State	Espírito Santo State	Maranhão State	Piauí State	Total

Measured	9,556,000	296,124,636	670,788,409	42,748,007	1,019,217,052
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	1,355,157,240

It is important to note that Northeast Brazil (Zone A; Figure 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) [65]. 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 [66] and later modified by Law n° 9314/1996 [67] and Law n° 13.575/2017 [68], 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 [69], 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 [69]. 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 [69,70].

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 [71], 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 [72]. 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 [73]. In addition, Law n°

9985/2000 [74] 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 [75]. 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 [76].

Several applications have been filed or are in progress for the research and exploitation of these resources (Figure 3). Moreover, some companies have already explored unique seabeds [8]. For instance, the 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 [62]. 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 [62]. 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 [77], 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 [62] and in 2020 the company doubled its turnover to 60 million [78, 79]. There are currently 12 mining concessions on the Brazilian continental shelf (Figure 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.

Table 2 - The production (ton) and production value (R$) of marine limestone in Brazil between 2013 and 2018. Source: Cavalcanti (2020) [8].

Year	Gross production (t)	Processed production (t)	Production value (R$)	Average selling price per ton (R$)
2013	20,045.70	10,986.45	6,948,354.00	662.72
2014	20,595.00	13,597.11	9,671,813.50	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	1,015.93

3.2 The threats to marine biodiversity and ecosystem services

Rhodolith banks 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 [61]. They also shelter a unique biodiversity, including reef fish [12, 18], ascidians, sponges [12], polychaetes [14], mollusks [80], corals [12], echinoderms [81], and crustaceans [80, 82]. Moreover, they act as seed banks for algal propagules and the larvae of invertebrates and vertebrates in other interconnected ecosystems [83], 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 [60], and extreme events, such as storms and energetic waves [84]. Moreover, overfishing by bottom trawling acts in tandem with these impacts to deteriorate the health and function of this ecosystem [85, 86]. 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 [87, 88]. 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 [89, 90]. Thus, efforts are to restore lobster stocks and fisheries sustainability, including the protection of habitats for refuge and nurseries, such as rhodolith beds.

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, 60]. 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 [53].

Rhodolith banks are the main habitat on the flattened tops of some seamounts in the VTC; Figure 2), such as the east Jaseur, Davis, and Dogaressa seamounts and on the insular platforms around the Trindade and Martim Vaz islands [91]. They are also abundant in the Abrolhos Region [92] and Fernando de Noronha Archipelago, which are the best known rhodolith banks to date [21, 51, 91]. These areas are considered biodiversity hotspots of high biological and socio-economic importance for conservation and human populations [93]. 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 carbonate mining. These rhodolith beds are mobile reef environments [18, 94], emphasizing once again the importance of these seascapes and the requirement for urgent and integral protection [80].

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 [95] and are essential for connectivity between the West Atlantic reef habitats [18, 53, 94]. For example, a large population of the endangered macroalgae *Laminaria abyssalis,* a habitat-forming species [96], grows on rhodolith nodules in a mesophotic environment between 45 and 120 m in depth [44].

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 [58,97] using offshore wind farms [98]. 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 [99]. In the Brazilian socio-economic context, it is important to emphasize that artisanal fisheries are responsible for more than 50% of national fish production [100] 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) [101].

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 [102].

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 [103]. 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, 61] 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 [104]. 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 [105].

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 (Figure 4).

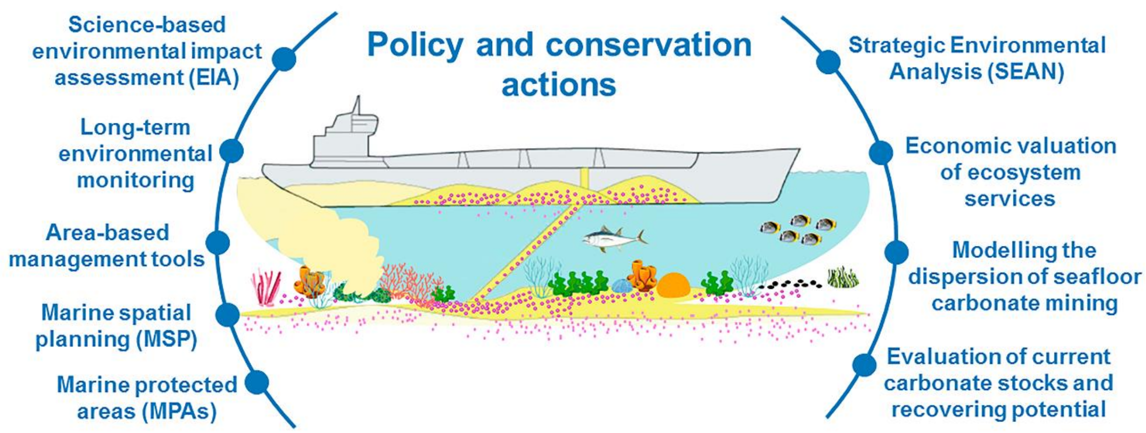


Figure 4 - Research, policy, and conservation actions for the rhodolith beds (Southwestern Atlantic, Brazil)

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 [93, 106] (Figures 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 [107, 108]. 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 [99]. 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 [109].

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 [110]. They are species vulnerable to overfishing, including due to biological characteristics of the species itself, such as late maturation and reproduction [111], 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 8,000 to around 352,000 $/ha/yr [109]. 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.

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5. CAPÍTULO 2 – Offshore wind farms as an emerging threats to tropical reef systems

Artigo será submetido para a revista "Nature sustentability".

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Abstract

Tropical reefs are currently the richest marine ecosystems, but they are threatened by anthropogenically-driven climate change. Reducing carbon emissions is one of the main milestones within the context of reef conservation. As a measure to reduce carbon emissions, offshore wind farms (OWFs) are gaining prominence. OWFs have been installed in temperate seas, and they are expected to soon be installed in tropical seas. However, since the ecological threat of OWFs within the context of tropical coasts has not been analyzed, there could have unforeseen and negative outcomes accompanying their installation. To address this issue, we tested the hypothesis that 18 large-scale OWFs to be installed in the Southwestern Atlantic could severely damage the ecological integrity reef systems in this region. Our results show that of the 18 OWFs, 15 of them (83.3%) are in areas with shallow and mesophotic tropical reefs, while the remaining three (16.7%) are going to be built less than 10 km away from reefs. OWFs are going to be installed at depths from 1.9m to 49m. In addition, 72% of the projects will be placed within 20 km of the distributional range of the lionfish (*Pterois* spp.), and 50% of them will near invasive corals (*Tubastraea* spp.). The 3,374 wind turbines to be installed will act as artificial reefs; this will be due to their close placement within a suitable habitat and depth. Therefore, the OWFs could act as a stepping stone for high-risk, invasive species, further damaging endemic tropical reef systems. The construction of OWFs on these shallow and mesophotic reef systems will also directly cause habitat destruction, increased water turbidity, noise pollution, and dispersion of sediment plumes; these are conditions widely recognized as negatively impacting reefs. Our results show that the poor placement of OWFs projects, a lack of marine spatial planning (MSP), and flawed environmental impact assessment

(EIAs) studies will negatively impact reef conservation efforts in tropical regions. Therefore, while the installation of OWFs is important for reducing greenhouse gas emissions, developing countries urgently need to implement MSP and science-based EIAs that address potential reef-associated impacts. Otherwise, OWFs may accelerate the ongoing degradation of tropical reefs.

Keywords: Renewable energy, Ocean Sustainability, Turbidity, Coral reef, Invasive species, *Lionfish*, *Tubastraea*

Introduction

Tropical reef systems are one of the most diverse, productive, and economically important ecosystems on Earth (Barlow et al., 2018). However, these marine ecosystems have been experiencing an ongoing and negative transformation due to global and local abiotic and biotic factors (e.g., global warming, ocean sprawl, and invasive species) (Hughes et al., 2017; Dixon et al., 2022). Specifically, these factors threaten ecosystem services provided by reef systems (Costanza, 2020; Costanza et al., 2014). These services include the provision of habitats for species of ecological and socioeconomic interest (e.g., fisheries) (Graham & Nash, 2003; Ortiz & Tissot, 2012), nutrient cycling (De Goeij et al., 2013), shoreline protection (Ferrario et al., 2014), recreation, and tourism (Spalding et al., 2017).

Between 1957 and 2007, the coral cover of tropical reefs across the globe is estimated to have decreased by 50% (Eddy et al., 2021). Additionally, these reefs have also lost structural complexity (Hughes et al., 2017), subsequently resulting in their inability to provide ecosystem services (Eddy et al., 2021). Anthropogenic carbon emissions and their effects, such as global warming, marine heatwaves, and ocean acidification, severely threaten reef systems (Lam et al., 2020; Frieler et al., 2013). Therefore, it is necessary to reduce the global reliance on fossil fuels. However, forecasts indicate that energy consumption will have increased by 50% in 2050 (IEA, 2019), causing an increase in greenhouse gas emissions, further accentuating negative and widespread reef-associated impacts. Thus, decarbonization of the energy matrix is urgent in the face of ongoing climate emergencies, and international treaties and actions to combat climate change, such as the Paris Agreement and COPs 26 and 27, are of utmost importance. In this context, clean energy sources such as solar and wind, which are considered low-carbon energy sources, within the context of eventually decarbonizing the global economy (Kothari et al., 2010).

Wind energy, both onshore and offshore, is gaining global prominence as an important alternative for the energy transition in line with decarbonization, as it has a great capacity to meet large-scale energy requirements (Decastro et al., 2019; Jafari et al. 2022; Khan et al. 2021; Papadis & Tsatsaronis, 2020). Offshore wind farms (OWFs) entail the deployment of wind turbines at sea. These wind farms have certain advantages over terrestrial one; for example, the low roughness of the sea surface, high and constant wind speeds, and the prospect of high rates of seafloor occupation due to the vastness of the economic-exclusive zones of countries (EPE, 2020). The global offshore wind energy market has grown by approximately 22% each year over the last decade, and new wind farm capacity is expected to increase by more than 235 GW, totaling 270 GW by 2030, with 70% of the total installed between 2026 and 2030 (GWEC 2021).

Traditionally, OWFs have been installed on the continental shelves of temperate regions (e.g., Europe), where carbonate sedimentation is reduced and the seafloor is usually formed by unconsolidated substrates, such as mud, sand, and gravel (Hammar et al., 2010). Europe, to date, is a global leader in the offshore wind farm market, with a total of approximately 16 GW installed and approximately 4,149 turbines in 11 countries, with the UK accounting for over 50% of this capacity, followed by Germany, hosting 40% of the European market (DeCastro et al., 2019). In temperate countries, increased scientific and technological developments in ocean sciences and robust environmental impact assessment (EIA) studies have provided a comprehensive theoretical foundation that allows for a strategic installation of OWFs. These strategies are applied with the intention of decreasing the impact of OWFs on vulnerable ecosystems (Ehler, 2021; Stelzenmullet et al., 2022). Furthermore, many temperate countries apply marine spatial planning (MSP) towards ensuring the sustainable installation and maintenance of OWFs (Ehler, 2021).

The MSP is an important tool recommended by UNESCO intended to facilitate the sustainable use of the marine environment. The MSP is supposed to encourage the development of blue economy, for example, by preventing the use and occupation of vulnerable marine ecosystems. Despite these advances in temperate countries, the impacts of OWFs have been detected on the marine biodiversity of these regions (reviewed by Galparsoro et al., 2022). Galparsoro et al. (2022) reported 867 findings on the pressure of OWFs across various ecosystem components in temperate regions. Biological pressures constituted most of the findings (63%); specifically, the most prominent elements of these biological pressures were those associated with biological disturbance (62%) and noise input (18%). A recent review reported that the most studied indicators were the impact of OWFs on animal behavior, fecundity, survival, mortality/injury rates, distribution, abundance, and biomass (Galparsoro et al., 2022). For example, in OWFs in Belgium, non-indigenous species have been found (e.g., mollusks and decapods), indicating that wind turbines pose invasion risks and can act as suitable habitats and stepping stones for non-indigenous marine species (Kerckhof et al., 2016; Mesel et al., 2015).

Owing to lower installation costs, subsidies for foreign companies by developing countries, and large areas with great offshore wind energy potential, numerous processes are underway for the large-scale installation of OWFs. Many developing countries, where the installation of OWFs is feasible, are in tropical regions (Soares et al., 2020). In these countries, coastal and marine zones have tropical reef systems in shallow (0-30 m) and mesophotic (30-150 m) zones. In addition, seafloor mapping in these countries is limited compared with that conducted in European or other developed countries (Purkins 2017). In addition, most of these countries do not have MSP (Santos et al. 2020), which are future targets in the Decade of the Ocean (2021-2030) and to address the Sustainable Development Goals (specifically, goal 14 - Life Below Water) (Ntona & Morgera, 2018). Therefore, we can hypothesize that the installation of OWFs in tropical countries, without proper marine spatial planning and a science-based understanding of reef distributions, can result in the ecological integrity of tropical reefs being threatened, for example, via habitat destruction and the introduction of invasive marine species.

Despite the strategic importance of the OWFs for ocean sustainability and global economic decarbonization, the potential threats of OWFs to tropical reefs have not been studied. In this study, we overlay 18 large-scale OWFs (consisting of 3,374 wind turbines) projects under environmental licensing on the Brazilian semi-arid coast (tropical SW Atlantic) with: (1) the current distribution of tropical reef systems, and (2) the current distribution of high-risk invasive species [i.e., lionfish (*Pterois* spp.) and the sun coral (*Tubastraea* spp.)]. Overall, we tested the hypothesis that OWFs, despite being a low-carbon energy alternative, could negatively impact tropical reefs by being stepping-stone habitats for invasive marine species, subsequently having a negative impact on the ecological integrity of tropical reef systems.

Results

Overlapping spatial data, using Geographical Information Systems approach, showed that of the 18 OWF projects to be constructed, 15 are in areas with shallow and mesophotic tropical reefs (Figure 1). Therefore, 83.3% of wind farm projects will installed in tropical reef areas of high biological and socioeconomic importance.

By analyzing projects that will not be in reef areas (n = 3), we found that the shortest distance between these projects and the nearest reef environment will be ~ 1.3 km, 2.2 km, and

13.5 km, respectively. Regarding the depth at which the wind farms will be installed; the depths range from 1.9 to 45 m (Appendix 1). Considering only the OWFs that will be installed on reef systems, nine of them reach maximum isobaths greater than 30 m, whereas four can reach up to more than 40 m, affecting unique mesophotic reefs.

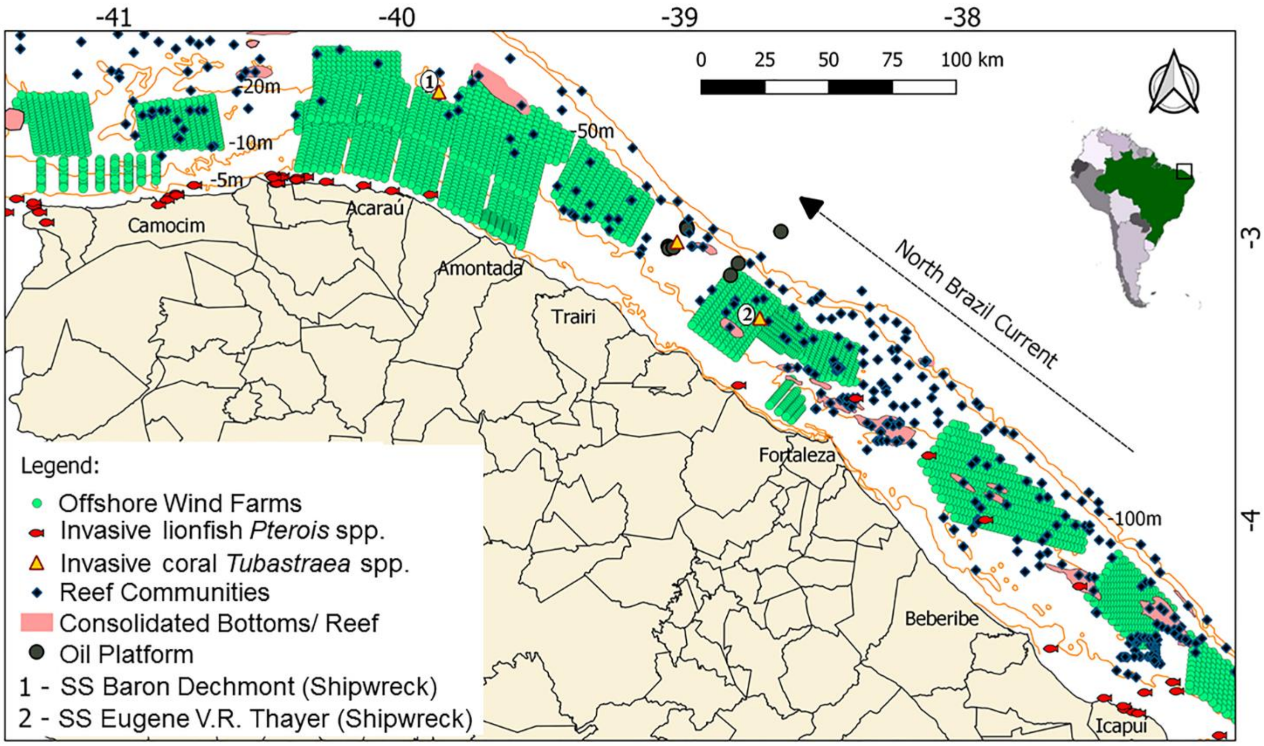

Figure 1 - The 18 potential OWFs projects. Reef systems are represented using blue dots and pink spots, while the occurrence of the invasive species lionfish, *Pterois* spp., and sun-coral, *Tubastrea* spp., are represented using red fishes and yellow triangles, respectively.

To analyze the distance between the potential OWFs projects and the occurrence of invasive species [i.e., lionfish (*Pterois* spp.) and sun-coral (*Tubastraea* spp.)], all distances were processed and expressed as (Figure 2). Most of the projects were located less than 20 km from the distributional ranges of the lionfish (n=13) (Figure 3A) and sun-coral (n= 9) (Figure 2).

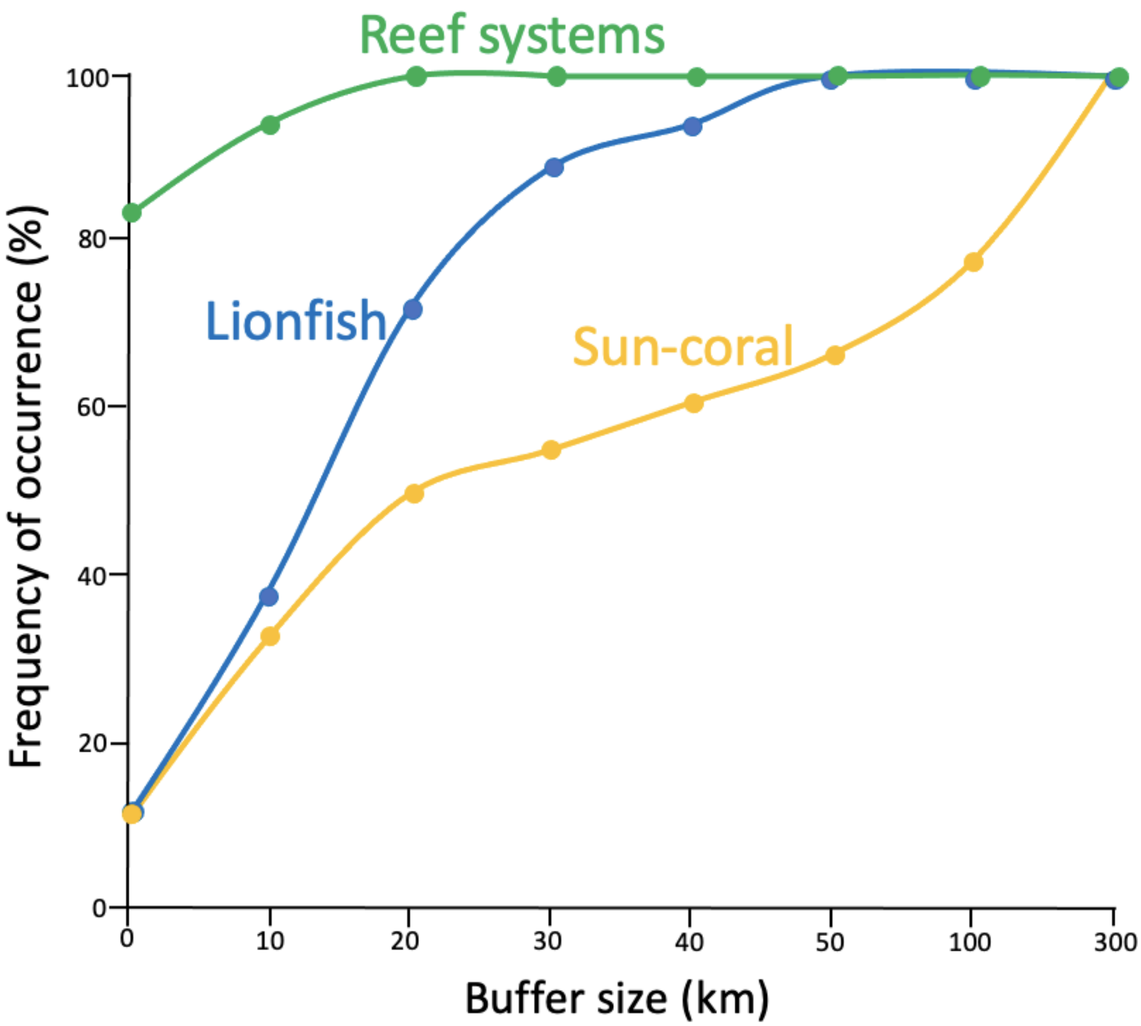

Figure 2 - The distance (km) between potential offshore wind farm projects on the equatorial SW Atlantic (Brazil) and reef systems (green line) and the distributional range of the invasive species [i.e., lionfish (Pterois spp.) and sun-coral (Tubastraea spp.)] (denoted with blue and yellow lines, respectively).

Discussion

We analyzed 18 potential large-scale OWFs in Brazil. We found that most of the areas chosen for these OWFs projects in the Tropical Southwest Atlantic overlap with the occurrence of tropical reefs (shallow and mesophotic). Moreover, these engineering projects overalp with the distributional ranges of invasive species [i.e., lionfish (*Pterois* spp.) and sun-coral (*Tubastraea* spp.)]. Thus, we are first to show that OWFs may generate direct and indirect threats to tropical reef systems, despite their benefits within the context of global decarbonization efforts via transitioning towards the wide-scale use of renewable energy sources. These threats include the direct destruction of reef systems through the building of fixed wind turbines above or near reef areas; whereas the indirect effects of these potential projects include their roles in acting as substrates (i.e., stepping-stones) for the range expansion of high-risk invasive species. Specifically, OWFs, can act as artificial reefs, supporting invasive corals and lionfish by providing food, shelter, etc. Therefore, it is essential to assess and mitigate the negative direct and indirect threats of OWFs in tropical reef systems and to have science-based marine spatial planning for the planned expansion of offshore wind energy in the planet's tropical seas.

Direct threats of OWFs to tropical reef systems

Traditionally (in temperate countries), OWFs are installed in unconsolidated bottom environments (e.g., sandy bottoms), which seem to favor fish aggregation, since they act as artificial reefs (Thurstan et al. 2010). However, the expansion of OWFs in regions with rocky bottoms, which are very common in warm tropical seas, can lead to the destruction of reef systems due to the attachment of towers above or close to the substrate and burial of reefs due to the dispersion of the sediment plume in excavations during the tower installation stage, as detected in OWFs in temperate seas (Galparsoro et al. 2022).

Our results highlight direct threats of these projects to tropical reefs; these threats show that the location of the potential OWF projects is only considered within the context of energy production (e.g., economic cost-benefit) and not their impact on marine ecosystems. These impacts are analogous to or worse than those seen in temperate ecosystems (Galparsoro et al., 2022). Overall, the potential OWF project will negatively impact the tropical reefs because the potential wind turbines are of the monopile foundation type (i.e., installed directly on the seabed) (IBAMA, 2022); additionally, OWFs change local hydrodynamics because the installation of turbines at the bottom requires dredging (Svane & Petersen, 2001; Hammer, 2008), and this changes the structure of various benthic communities. Additional anticipated impacts include the burial of reefs and death of their fauna, increased water turbidity, and reduced photosynthesis (Galparsoro et al., 2022). It is important to mention that there is also a risk of the resuspension of toxic compounds (i.e., previously stagnant on the seabed) into the water column, causing toxicity to organisms (Hammer, 2008). However, this aspect requires further evaluation through field and laboratory analyses, mainly in EIAs. In addition, it is important to consider that the nine evaluated potential OWFs are in areas where reef systems occur and reach depths greater than 30 m. Reef systems above these depths are already configured as mesophotic ecosystems, which are considered ecological refuges for species in the face of anthropogenic impacts; overall, the conservation of these reef systems must be prioritized (Rocha et al. 2018).

Noise pollution on the seabed associated with the installation and operation of OWFs is also likely to impact the tropic reefs. This impact has been widely reported in ongoing projects in temperate seas worldwide (Galparsoro et al., 2022). The noise generated by the wind turbines may be associated with the attachment of their structures to the seabed or the vibrational noise from the operation of the machinery and blades through the passage of airflow, which radiates into the water column and seabed (Madsen et al. 2006). There have been studies pointing to behavioral changes, disorientation, and death of marine mammals, turtles, and fishes due to excessive noise, especially during the installation of turbines (Epe, 2020; Hammar et al. 2016; Madsen et al., 2006; Tougaard et al., 2009). Additionally, migratory birds have been shown to collide with turbine propellers, or even change their migration route (Desholm & Kahlert, 2005; Grecian et al., 2010). Within the context of this study, the studied potential infrastructural development is in line with the migratory route of *Calidris ferruginea*, a shorebird that migrates from the northern region of the Northern Hemisphere and takes refuge in this tropical region (Musher et al. 2016). Although studies regarding these types of impacts are still scarce (Galparsoro et al. 2022), they are expected to be relevant in areas of biological importance (Hammer et al. 2008).

Of the 18 projects under analysis, two were more advanced and had already delivered the EIA to the licensing environmental agency. In these studies, a serious flaw was observed because they did not cite the occurrence of reef systems. Thus, it is easy to speculate that these EIAs do not have a scientific basis and do not provide high-resolution maps to overlay engineering designs with tropical marine ecosystems. This failure denotes the lack of prediction of the impacts discussed here, such as the role of OWFs as stepping stones for invasive species and direct impacts (e.g., habitat destruction, turbidity, and burial) on tropical reefs. EIA studies are inconsistent and lack primary data collection by field surveys (by diving, ROVs, or data from scientific literature). The EIAs are only focused terrestrial environment, and the impacts highlighted are only point to the possibility of burying mostly sedentary benthic organisms and impacting the migratory route and settling of avifauna; however, these reports do not touch on the existence of tropical reefs or invasive species in the area. In EIAs, the creation of new substrates (e.g., artificial reefs using OWFs) is only seen as a positive change. Despite the possible benefits of artificial reefs in sandy bottoms (Hammond et al. 2020; Higgins et al. 2022), it is essential to highlight that the discussion of this topic in the study reef area requires special attention owing to the presence of invasive species.

This prediction from EIAs is completely incongruent with scientific knowledge that clearly shows that artificial reefs act to expand the dispersion of sun corals and lionfish in the South Atlantic (Soares et al. 2020; Coelho et al. 2022; Soares et al. 2022). Furthermore, EIAs only consider the impact of individual projects. OWFs can considerably decrease the wind force on the water surface, which leads to local and regional hydrodynamic changes, including temperature, salinity, and sediment transport (Berkel, et al., 2020; Christiansen et al., 2022). On a local scale, the effects of these changes on the biota are not always clear (Berkel, et al., 2020). However, in the case in question, it is important to consider the cumulative and synergistic effects of the set of 18 OWFs (Figure 1), as these effects become relevant at larger scales (Berkel, et al., 2020). Thus, considering that approximately 37% of the analyzed continental shelf will contain OWFs, the impacts of changes in hydrodynamics on the reef systems in the region are expected to be significant and require further evaluation. These environments are typically exposed to a moderate and unidirectional current throughout the year, are subject to complex sedimentary dynamics, and, as a rule, receive low inputs of continental fresh water (Morais et al., 2019; Carneiro et al., 2022). Large-scale alterations in regional hydrodynamics can therefore hamper the migratory flows of reef species and increase the risk of burial, which can have drastic consequences for reef systems endemic to the region.

Indirect threats of OWFs to reef systems: Stepping-stones for invasive species

Offshore wind farms can act as artificial reefs by providing hard substrates that favor the growth of benthic organisms. Specifically, OWFs can act as new habitats that can serve as feeding, reproductive, and nursery seascapes for native and non-native species (Petersen & Malm, 2006). The development of fouling communities (benthic encrusting assemblages) on wind turbines (Wahl

& Hopp, 2002; Galparsoro et al., 2022), is directly associated with the type of building material, usually concrete or steel (Mathern; Haar; Marx, 2021), as well as its chemical composition (Bavestrello et al., 2000) and roughness (Skinner; Coutinho, 2005). The reef effect of OWFs poses a risk by also providing habitats for invasive species because of the availability of space and by altering competition and predation patterns among species (Madsen et al. 2006); this is a trend that has already been observed in temperate seas (Galparsoro et al., 2022). In the tropical environments under analysis, there is a high risk of introducing sun corals (*Tubastraea coccinea* and *T. tagusensis*) into OWFs, as these invasive species have high recruitment rates on artificial substrates, such as concrete and metal (Creed & Paula 2007) which are common in fixed wind turbines. Furthermore, there is a high risk that OWFs act as stepping stones for the lionfish (*Pterois* spp.). These predicted are rooted in the recent and rapid invasion of this species in the South Atlantic, particularly in artificial reefs (Soares et al. 2022).

The distance between OWFs and natural tropical reefs is a determinant for understanding the composition of both environments, as there is an exchange of larvae, adults, and juveniles between the two entities (Petersen & Malm 2006); this exhange is primarily due to the fast currents in the region (Carneiro et al., 2022). The constitution of this new (and artificial) habitat can modify local biodiversity, as well as attract opportunistic (Bacchiocchi & Airoldi 2003) and invasive species (Glasby & Connnell, 1999). In this regard, OWFs can act as stepping-stones for these invasive species (Glasby & Connnell, 1999), as the same dynamics have been seen in shipwrecks, oil platforms, and other man-made environments (Saura et al., 2014). A major threat to native biodiversity in the studied region is the coral *Tubastrea* spp., known as sun (or orange-cup) coral (Paula & Creed, 2004), and the lionfish *Pterois* spp. (Soares et al., 2022), both of which are present in reefs where OWFs are to be potentially installed (Figure 2).

Tubastraea invasive corals are major competitors with native species on South Atlantic coral reefs, such as the reef-building coral, *Mussismilia hispida*, which catalyzes a decrease in the abundance of native organisms (Riul et al. 2003). As invasive corals with a high recruitment and substrate occupancy rates (Paula & Creed 2005; Mizrahi 2008; Mantelatto et al. 2011), *Tubastraea* cause drastic changes in the structure of tropical benthic communities (Lages et al. 2010, 2011). Nine of the OWFs projects occurred within only 20 km within the distributional range of *Tubastraea tagusensis* and *T. coccinea* (50% frequency of occurrence) (Figure 2). These invasive coral species can exhibit a short pelagic period and fast recruitment for as little as three days (Glynn et al. 2008), but *Tubastraea* also exhibits a cluster formation of adult colonies in the water column, which increases the chances of long-distance dispersal (Mizrahi et al. 2014). Under laboratory conditions, *T. tagusensis* larvae prefer to settle on cement surfaces rather than on ceramic or iron surfaces (Creed & De Paula, 2007). Due to the low financial costs and durability of the material (Fernandez & Pardo, 2013), the base of offshore wind turbines is likely to be a suitable environment for the recruitment of these invasive corals, as these bases usually consist of concrete or steel (Mathern et al. 2022). Moreover, this substrate preference of invasive corals highlight the vertical surfaces of wind turbines as other suitable habitats, such as columns of oil and gas platforms (Mangelli & Creed, 2012). This hypothesis of the future occupation of OWFs by *Tubastraea* spp. is supported by the current records of these invasive species in shipwrecks and oil and gas platforms in the region (Soares et al., 2016; 2020; Creed et al., 2017).

Another recent biological invasion recorded on the Brazilian coast, mainly where the OWFs will be installed, is that of the lionfish (*Pterois* spp.) (Soares et al. 2022). This is a new, ongoing, and severe invasion in the South Atlantic (Linardich et al., 2021), as lionfish present themselves as both predators and competitors (Albins & Hixon, 2011), and they can cover approximately 10 km in 10 days (Green et al. 2021). These species are present in two areas where there are plans to install wind farms, and in seven OWFs projects will be less than 10 km from the distributional range of this invasive species. These species are generalist predators and are a strong threat to native fauna, such as fish and crustaceans (Albins & Hixon, 2011; Albin & Hixon 2008), including preying on commercially important species such as groupers and snappers (Albin & Hixon 2008). In addition to the lack of natural predators, lionfish are resistant to competition and parasitism (Albins & Hixon, 2011), which makes controlling their populations difficult. As an indirect impact, lionfish disrupt the stability of reef species, as they can prey on herbivorous species, such as parrotfish (Mumby et al. 2006). The predominant occurrence (58%) of records in artificial reef environments in this region and depths (Soares et al., 2022) clearly shows the high risk of OWFs (i.e., those that will be built at depthds of 1.9 and 45 m depth) to act as stepping-stones, furthering increasing the geographical range of lionfish, and the risk of invasion of natural reefs in the region (Carneiro et al., 2022).

In the Tropical South Atlantic, the impact of lionfish and sun coral invasion can be drastic (Ferreira et al., 2015; Creed et al., 2017; Soares et al., 2022) for reef systems, mainly because of the already-low coral richness and the high degree of endemism (Halpern & Floeter, 2008). As these invasive species easily live associated with artificial reefs (Albins & Hixon, 2010, Soares et al., 2022), and because the analyzed area has currents that flow rapidly to the Northwest direction at speeds of approximately 0.15 $m.s^{-1}$ (Texeira and Machado, 2013; Dias et al., 2016), the creation and misplacement of 18 large-scale OWFs can clearly collaborate to the dispersal of these invasive species in this study area. This reef region has great biogeographic relevance because of its connection with the Caribbean and Amazonian reefs (Carneiro et al., 2022). Thus, the current planning of OWFs in this low-latitude region also poses a threat to the Amazon mesophotic reefs (Moura et al. 2016) and a large portion of the South American reef system (Carneiro et al., 2022) because of possible impacts on connectivity processes and native biodiversity, as already detected in OWFs already installed in temperate countries (Galparsoro et al., 2022).

Conclusions

This study was the first to show that if offshore wind farm developments are poorly planned and located, they can pose a direct threat to tropical reefs or indirectly impact them by acting as stepping-stones for invasive species. These impacts have already been recorded in temperate regions (Galparsoro et al., 2022). For the tropical area in question, the risk is high for burial and impacts on reef habitats and communities, as well as range expansion of invasive species such as sun coral and lionfish.

Thus, marine spatial planning with a focus on the maintenance of ecological integrity and rigorous environmental impact studies (EIA) are important strategies (i.e., not yet implemented in several tropical countries) to map marine ecosystems. In this study, we showed that Brazil still does not have marine spatial planning or science-based EIAs, which increases the risk of misplacement of OWFs in areas of relevant biological and socioeconomic importance. In the case of wind farms, the use of these two strategies could allow for the relocation of the potential OWFs, preventing their installation in areas of biological importance. While the installation of OWFs is important for reducing greenhouse gas emissions, tropical countries urgently need to implement marine spatial planning and science-based EIAs that address the impact of these projects on these reef systems and related habitats (e.g., rhodolith beds, seagrass beds, and mangroves). These efforts are necessary since offshore wind farms could accelerate the ongoing degradation of tropical reefs in the world's oceans.

Material and methods

Study area

The tropical reefs on the Southwestern Atlantic coast are extensive, spread along 4,000 km of coast, and are separated from the Caribbean reefs by the Amazon and Orinoco Rivers. They exhibit low coral diversity (23 species), but high rates (~34%) of coral endemism (Leão et al. 2003; 2016). These reefs are part of a single extensive reef system known as the South American reef system (Carneiro et al., 2022). This reef system consists of three main parts: the Amazon reefs (extending for ~1,000 km), semiarid coast reefs (1,000 km), and Eastern Brazilian coast reefs (2,000 km) (Figure 1) (Carneiro et al., 2022).

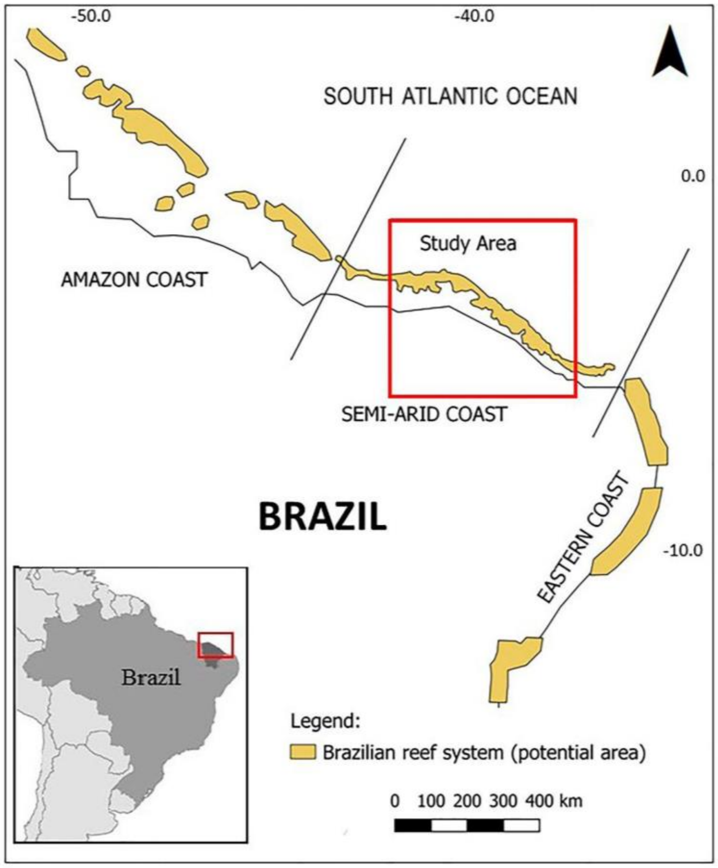

Figure 3- Study area on the Brazilian semiarid coast: Tropical reef systems on the South Atlantic Ocean (South American Reef System according to Carneiro et al. 2022).

Because of the high potential for offshore wind power generation due to wind speed and stability and the greater number of OWFs (18 large-scale projects) under environmental licensing (IBAMA, 2022) in the SW Atlantic, our focus was on the Brazilian semiarid coast (Figure 1). This low-latitude region is in the easternmost tip of South America and is projected over the equatorial South Atlantic region. This coastal region is home to a unique set of seascapes and fishing communities and is the only stretch of the Brazilian coastline under the increasing direct influence of the semi-arid climate (Muehe, 2010). It encompasses a variety of features such as estuaries, seagrass and rhodolith beds, dunes, tropical shallow and mesophotic reefs, and mangroves (Barros et al., 2016; Godoy et al., 2015; Pinheiro et al., 2016; Carneiro et al., 2022). This region of interest for offshore wind potential is influenced by the intertropical convergence zone (ITCZ), which is a zone of convergence at low levels of the northeast trade winds from the Northern Hemisphere, and the Southeast trade winds from the Southern Hemisphere, which determine the rain and wind regimes in this region, which is seasonal and reaches average speeds of 7.75 m/s in the dry season of the year (August through December) (Maia et al. 2001).

The study area comprised the Equatorial SW Atlantic region, specifically the coast of Ceará State (Northeast Brazil) (Figure 1). The Ceará coastline (2°S–7°S and 37°W–41°W) has a length of 573 km (Pinheiro et al. 2016). Currently, on the coast of Ceará, according to the IBAMA (2022), there are 18 OWFs under environmental licensing, of which Caucaia – Bi Energia (48 towers - 576 MW), Jangada (200 towers - 3.000 MW), Camocim (100 towers - 1.200 MW), Dragão do Mar (128 towers - 1.216 MW), Alpha (400 towers - 6.000 MW), Costa Nordeste Offshore (256 towers - 3.840 MW), Asa Branca I (72 towers - 1.080 MW), Sopros do Ceará (200 towers - 3.000 MW), Projeto Pecém (215 towers - 3.010 MW), H2GPCEA (200 towers - 3.000 MW), Projeto Colibri (134 towers - 2.010 MW), Projeto Ibitucatu (134 towers - 2.010 MW), Asa Branca II (72 towers - 1.080 MW), Ventos dos Bandeirantes (229 towers -2.748 MW), Asa Branca III (288 towers - 4.320 MW), Asa Branca IV (288 towers - 4.320 MW), Araras Geração Eólica Offshore (200 towers - 3.000 MW) and Tatajuba Geração Eólica Offshore (200 towers - 3.000 MW). These 18 potential projects totaled 3,364 towers, with a potential of 48,410 MW. In Brazil, potentially polluting activities go through an environmental licensing control regulated by resolution 01/1986 of the National Environment Council (CONAMA, 1986) and are subject to the Environmental Impact Study (EIA) as a basic instrument for licensing, as in other parts of the world. In this study, we used geo-referenced data from these 18 OFMs projects licensed by IBAMA.

Data analysis

The data and vectors of the 18 OWFs projects in the licensing process were obtained from the Brazilian Institute for the Environment and Renewable Natural Resources (IBAMA), which is available online in detail (http://www. ibama. gov. br/laf/consultas/mapas-de-projetos-em-licenciamento-complexos-eolicos-offshore). The cartographic representation of these vector files was performed using QGIS software for the base map. The occurrence and spatial distribution of tropical shallow and mesophotic reefs in the study area were obtained by compiling data and mapping, as previously published by Morais et al. (2020), Pinheiro et al. (2020), and Carneiro et al. (2022). The term “reef systems” is used in the text to designate the set of consolidated bottoms/reefs and reef communities according to the definitions and mapping of Carneiro et al. (2022).

The current distribution of the invasive sun corals (*Tubastraea coccinea* and *Tubastraea tagusensis*) in the study area was obtained by Soares et al. (2016), Soares et al. (2020), and Braga et al. (2021), while lionfish records (*Pterois* spp.) were obtained by Soares et al. (2022). Information on invasive species, tropical reefs, and 18 OWFs was compiled, overlaid, and represented using maps. Spatial overlay analysis and map generation were done through the QGIS 3.14 software, using the geographic coordinate system EPSG:4674 Sirgas 2000 UTM 24S, at the final representation scale of 1:1750000; please note that the graphic scale was set at 25 km intervals to facilitate interpretations. The creation of the map's layout was mainly based on the vector files added as kml and/or shapefiles (e.g., wind farms and isobaths). The map was saved as a TIF file with an export resolution of 300 dpi. The number of offshore wind farm installation projects inside buffer zones with distinct widths (i.e., from 0 to 300 km) from the occurrences of sun coral and lionfish were calculated using QGIS software to produce the figure 2. Different offshore wind farm projects are indicated on the map with the same color to ensure confidentiality; however, specific projects can be seen publicly in IBAMA (2022).

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Supplementary Information

Supplementary Table S1 - Distances between OWFs, reef systems, the occurrence of sun coral and lionfish, and the bathymetric range of occurrence in the OWF.

OWFs	Parques em Sistemas recifais	Distance between OWF and consolidated bottoms (km)	Distance between OWF and reef communities (km)	OWF on reef systems or near (km)	Distance between sun coral records points and OWF (Km)	Distance between lion fish records points and OWF (Km)	Bathymetric range of occurrence in the OWF (m)
OWF 1	Presence	0	4.8	0	26.5	13.6	12-24 m
OWF 3	Presence	0	0	0	16.5	48.3	18-45 m
OWF 4	Absent	14.5	2.2	2.2	113	5.7	6-17 m
OWF 5	Absent	16.5	1.3	1.3	7.8	17	8-22 m
OWF 6	Presence	0	0	0	83	0	12-36 m
OWF 7	Presence	0	0	0	5.4	19.8	12-41 m
OWF 8	Absent	30	13.5	13.5	41.5	23.9	7-15 m
OWF 9	Presence	0	0	0	4.3	6.5	20-37 m

OWF 10	**Presence**	**3.2**	**0**	**0**	**0**	**20.3**	**22-38 m**
OWF 11	**Presence**	**0**	**0**	**0**	**0**	**10.4**	**14-42 m**
OWF 12	**Presence**	**0**	**0**	**0**	**206**	**4.8**	**10-30 m**
OWF 13	**Presence**	**10**	**0**	**0**	**16.5**	**36**	**14-31 m**
OWF 14	**Presence**	**11.7**	**0**	**0**	**32**	**26**	**14-27 m**
OWF 15	**Presence**	**0**	**0**	**0**	**166**	**4.7**	**12.5-43 m**
OWF 16	**Presence**	**12.2**	**0**	**0**	**3.3**	**0**	**1.9-26 m**
OWF 17	**Presence**	**19**	**0**	**0**	**12.8**	**2.5**	**2.7-27 m**
OWF 18	**Presence**	**0**	**6.4**	**0**	**138**	**19.3**	**11-25 m**
OWF 19	**Presence**	**13**	**0**	**0**	**88**	**18.5**	**9-19 m**

6. CONCLUSÕES E CONSIDERAÇÕES FINAIS

O presente trabalho analisou o impacto de duas importantes atividades da economia azul em ecossistemas marinhos de grande relevância biológica e socioecômica. O primeiro capítulo discutiu sobre o impacto da mineração de carbonatos marinhos ativos no país, que estão em áreas potenciais de ocorrência de grandes bancos de rodolitos. Esses ambientes fornecem inúmeros serviços ecossistêmicos e são áreas de ocorrência de espécies de importância ecológica e econômica. Além disso, essa atividade de exploração do fundo marinho pode entrar em conflito com outras atividades da economia azul, como a pesca. O segundo capítulo mostrou pela primeira vez que a implantação dos parques eólicos *offshore* no Brasil ameaçam os sistemas recifais tropicais, por estarem projetados em cima ou bem próximo aos ecossistemas recifais, bem como, por poderem atuarcomo *stepping stones* (riscos indiretos) de espécies invasoras como o peixe-leão e o coral-sol. Apesar dos parques eólicos *offshore* desempenharem papéis importantes na redução da emissão de gases de efeito estufa, este empreendimentos podem acelerar a degradação dos recifes tropicais.

Nossos resultados constataram que os estudos de impacto ambientais dessas atividades são falhos, não evidenciando os riscos apresentados anteriormente, ou mesmo não apresentando alternativas adequadas e exequíveis de recuperação dos ecossistemas após os impactos. Há uma grande lacuna de estudos científicos sobre o fundo marinho e, por isso, é fundamental que a exploração desses recursos seja feita de forma sustentável, baseada em evidências científicas e sem impactos sociais e biológicos significativos. Políticas de ações de conservação marinha, como robustos Estudos de Impacto Ambiental (EIA), também baseados em evidencias cientificas, monitoramento a longo prazo, planejamento espacial marinho ao longo da costa brasileira, criação de novas áreas marinhas protegidas, avaliação dos serviços ecossitêmicos, modelagem de dispersão do fundo marinho, avaliação dos estoques e potencial de recuperação, criação de novas áreas marinhas protegidas, dentre outras políticas de conservação, são necessárias para promover a exploração desses recursos de forma sustentável.

Desta forma, é imprescindível conhecer a real dimensão dos impactos dessas atividades e, para isso, os EIA precisam ser elaborados com maior qualidade de dados e discussão, principalmente face às mudanças climáticas. Por o Brasil não ter um planejamento espacial marinho, essa medida desponta manifestadamente para preservação de áreas de importância biológica. Se não há estudos robustos que resguardem esses ecossistemas, bem como o fornecimento de seus serviços ecossitêmicos, é mais prudente prezar pelo princípio da precaução e evitar a exploração insustentável desses recursos e ambientes como preconizado pela verdadeira Economia Azul.

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Full length article

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

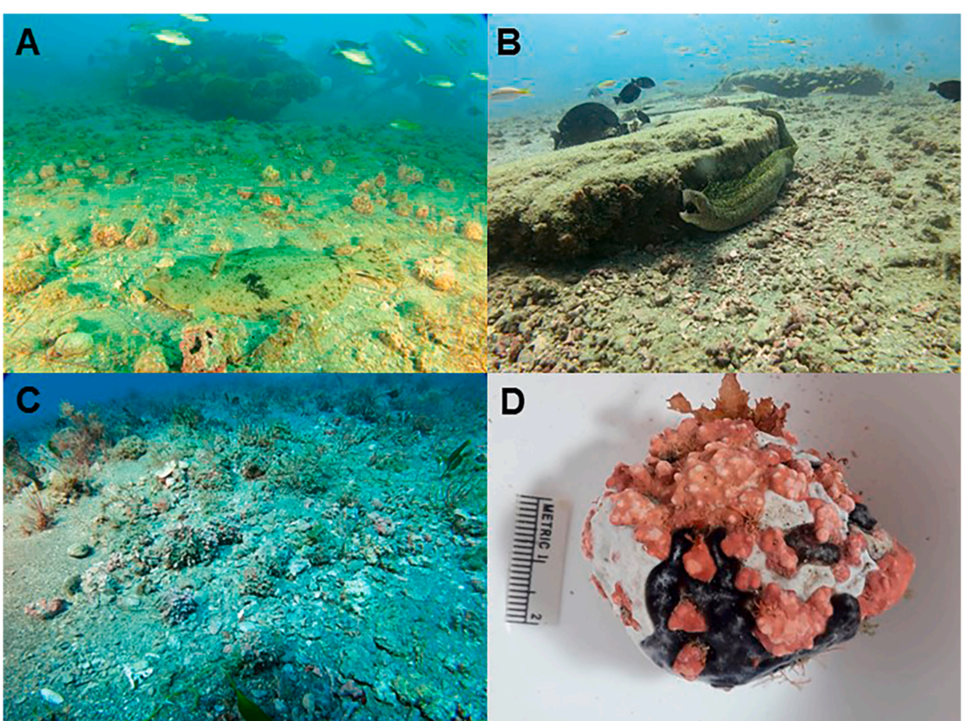

Fig. 1. The biodiversity that is associated with the complex three-dimensional seascape which is structured by rhodolith beds in the South Atlantic Ocean. (A, B) – Demersal fish associated with the rhodolith bottom (*Bothus* sp. and *Acanthurus chirurgus*), (C) - Epilithic macroalgae and seagrasses associated 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.

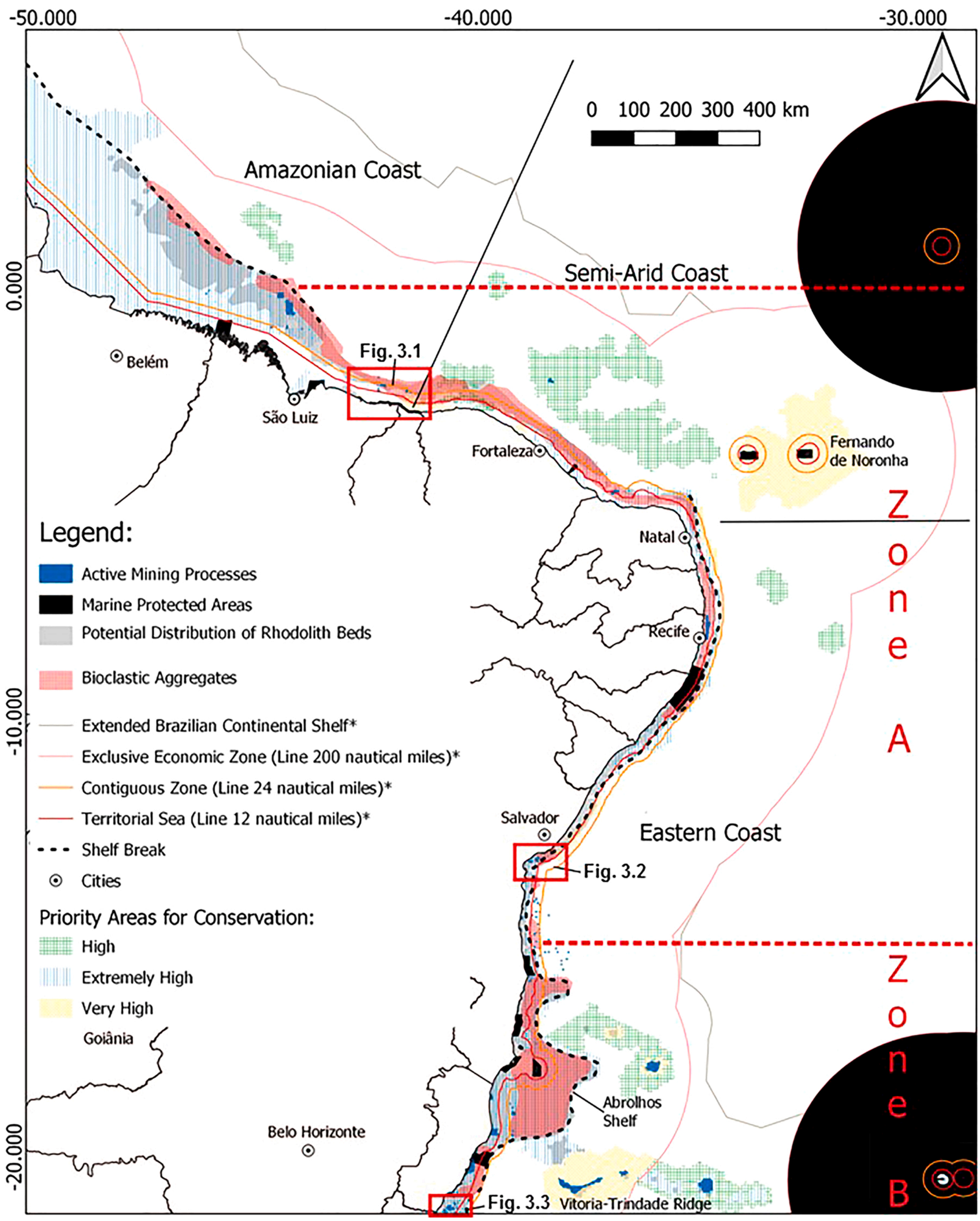

Fig. 2. Active mining processes, carbonate bottoms, and marine biodiversity hotspots along the Brazilian coast: the Amazonian shelf to the Vitoria-Trindade Ridge. This figure highlights active mining processes, marine protected areas, and priority areas for conservation [27,42-47]. Zones A and B refer 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

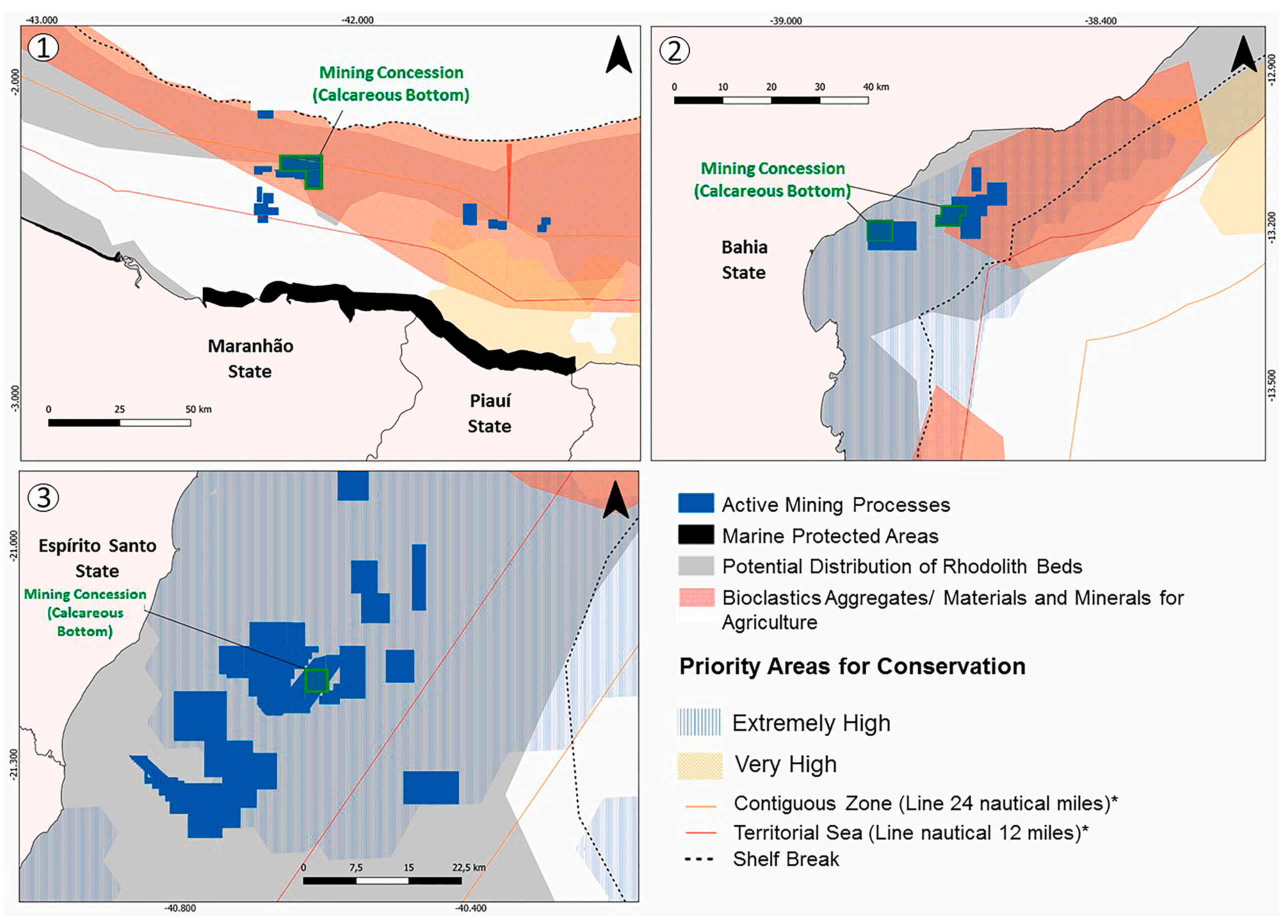

Fig. 3. The active process highlighting the mining concessions that overlap or are close to the rhodolith beds, marine protected areas, and priority areas for the conservation of the tropical marine biodiversity (South Atlantic, Brazil) [27,42-47]. (3.1) Maranhão and Piauí coast; (3.2) Bahia coast; and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

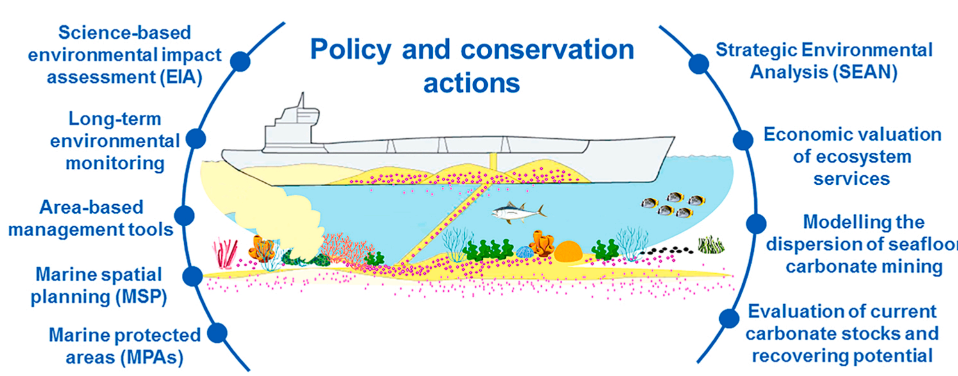

Fig. 4. Research, policy, and conservation actions for the rhodolith beds (Southwestern Atlantic, Brazil).

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.

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