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PROTEÇÃO À LINHA DE COSTA POR RECIFES DE CORAL DO ARQUIPÉLAGO DE TINHARÉ-BOIPEBA, BAIXO SUL DA BAHIA, FRENTE A MUDANÇAS CLIMÁTICAS

CARLA ISOBEL ELLIFF

SALVADOR

2019

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Carla Isobel Elliff

Orientadora: Profa. Dra. Iracema Reimão Silva

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CARLA ISOBEL ELLIFF

"PROTEÇÃO À LINHA DE COSTA POR RECIFES DE CORAL DO ARQUIPÉLAGO DE TINHARÉ-BOIPEBA, BAIXO SUL DA BAHIA, FRENTE A MUDANÇAS CLIMÁTICAS"

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TESE APROVADA PELA BANCA EXAMINADORA:

Iracema Reimão Silva

Dra. Iracema Reimão Silva
Orientadora – UFBA

Junia K. Guimarães

Dra. Junia K. Guimarães
Examinadora Externa – UFBA

Dra. Janini Pereira
Examinador Externo – UFBA

Dr. José Rodrigues Souza Filho
Examinador Externo – IFBaiano

Dr. Ricardo Piazza Meireles
Examinador Interno – UFBA

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RESUMO

A proteção à linha de costa é um dos serviços ecossistêmicos mais relevantes fornecidos por recifes de coral. No entanto, o conhecimento sobre esse processo ainda se encontra fragmentado na literatura atual, com lacunas importantes para compreender como se dá o fornecimento desse serviço por esses ecossistemas diante de cenários de mudanças climáticas. O objetivo geral do presente projeto foi fornecer cenários de mudanças no nível de proteção à linha de costa pelos recifes de coral do Arquipélago de Tinharé-Boipeba, BA, baseado em projeções de subida do nível do mar dentro do contexto das mudanças climáticas. Modelagens de dinâmica costeira atual foram realizadas usando o conjunto de ferramentas computacionais fornecido pelo sistema de modelagem costeira SMC-Brasil. Os recifes de coral em franja demonstraram alta eficiência em atenuar a energia das ondas incidentes mesmo em condições energéticas durante a maré alta no cenário atual. O SMC-Brasil também foi utilizado para modelar taxas de subida do nível do mar para os anos-horizonte de 2070 e 2100. Estes valores ficaram em 6 mm/ano no cenário mais conservador e 8 mm/ano para o cenário mais pessimista. Estas taxas foram aplicadas ao modelo de vulnerabilidade costeira a erosão e inundação do *software* Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) em cenários com e sem recifes de coral, de modo a avaliar qualitativamente a contribuição desse ecossistema. O arquipélago foi classificado como tendo vulnerabilidade intermediária atualmente, com diversas áreas de importância socioeconômica se tornando altamente vulneráveis caso os recifes de coral não forneçam mais o serviço de proteção. Estratégias de gestão costeira devem buscar aumentar a resiliência dos recifes através da redução dos impactos locais. Além disso, dados ambientais e socioeconômicos devem ser melhor disponibilizados para permitir tomadas de decisão baseadas em evidências. Por fim, sugere-se que protocolos de avaliação internacionais de recifes de coral devam incluir informações geomorfológicas além de dados biológicos.

Palavras-chave: modelagem costeira; serviços ecossistêmicos; gerenciamento costeiro; subida do nível do mar; erosão.

ABSTRACT

Shoreline protection is one of the most relevant ecosystem services delivered by coral reefs. However, knowledge on this process is still quite fragmented in current literature, with important gaps regarding how this service is delivered by these ecosystems in the face of climate change scenarios. The overall objective of the present project was to generate scenarios of changes to shoreline protection by coral reefs in the Archipelago of Tinharé-Boipeba, BA, based on sea-level rise projection due to climate change. Coastal dynamics modelling was conducted using the set of computational tools within the coastal modelling system SMC-Brasil. Fringing coral reefs showed high efficiency in attenuating wave energy even under energetic conditions during high tides in the current scenario. SMC-Brasil was also used to model sea-level rise scenarios for the horizon years of 2070 and 2100. The values found were 6 mm/year in the conservative scenario and 8 mm/year in the pessimistic scenario. These sea-level rise rates were used in the coastal erosion and flooding vulnerability model from the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) software in scenarios with and without coral reefs, so to qualitatively evaluate the contribution of this ecosystem. The archipelago was classified as intermediately vulnerable currently, with several socioeconomically important areas becoming highly vulnerable if coral reefs are unable to deliver shoreline protection. Coastal management strategies should seek to increase coral reef resilience by reducing local impacts. Moreover, environmental and socioeconomic data should be more available to allow evidence-based decision-making. Finally, international coral reef monitoring protocols should include geomorphological information in addition to biological data.

Keywords: coastal modelling; ecosystem services; coastal management; sea-level rise; erosion.

SUMÁRIO

CAPÍTULO 1
INTRODUÇÃO GERAL

Serviços ecossistêmicos podem ser entendidos simplificadamente como os benefícios fornecidos por ecossistemas à sociedade. Dentre os serviços costeiros mais notáveis listados pelo Millennium Ecosystem Assessment (2005) estão a provisão de alimento e matéria prima, recursos genéticos, manutenção de habitats, assimilação de poluentes, regulação climática, ciclos biogeoquímicos, oportunidades para recreação e lazer, e a proteção à linha de costa.

Costanza et al. (1997) em seu trabalho clássico demonstraram que ambientes costeiros são responsáveis por 63% do valor total de todos os serviços ecossistêmicos globais. Mais recentemente, Costanza et al. (2014) avaliaram as mudanças nestes valores estimados há mais de duas décadas e encontraram um aumento no valor de serviços ecossistêmicos costeiros, apesar de perdas na área de diversos habitats costeiros. Este achado denota a crescente importância dos ecossistemas costeiros para o desenvolvimento humano, particularmente dentro do contexto dos chamados *blue economy* e *blue growth* (economia azul e crescimento azul).

Além disso, Gordon e Barron (2013) afirmam que a maioria dos serviços listados pelo Millenium Ecosystem Assessment (2005) são direta ou indiretamente influenciados por fatores e processos geológicos, hidrogeológicos e geomorfológicos. Esta relação tem tornado o estudo dos serviços ecossistêmicos um componente importante em investigações do Quaternário, principalmente considerando que a geosfera representa a base sobre a qual toda a biosfera se sustenta (Elliff e Kikuchi, 2015).

Dentre os ambientes costeiros de maior relevância no fornecimento de serviços estão os recifes de coral. Existe uma ampla literatura explorando os diversos valores dos recifes de coral para a sociedade, o que demonstra claramente a importância inerente destes ecossistemas ao bem-estar humano (e.g. Costanza et al., 1997; Moberg e Folke, 1999; Principe et al., 2012; Arkema et al., 2013; Costanza et al., 2014; Elliff e Kikuchi, 2017).

Os recifes brasileiros apresentam características que os diferem notavelmente de outros recifes no mundo, como as altas taxas de endemismo e baixa diversidade de espécies, além de serem capazes de se desenvolverem na presença de sedimentos siliciclásticos lamosos nos bancos recifais mais costeiros (Leão et al., 2003). Este pode ser considerado um fator estressante para a comunidade coralinácea que depende de boa luminosidade na água para garantir energia por meio da fotossíntese realizada por suas algas simbiontes, as zooxantelas. Com relação a fatores estressantes, Moberg e Folke (1999) afirmam que a recuperação dos recifes frente a impactos humanos persistentes (e.g. poluentes, descargas de sedimentos) é mais lenta do que frente a impactos naturais (e.g. furacões, surto de predadores). Os impactos cumulativos de diversos fatores ligados a mudanças climáticas (mudanças em regimes de chuvas, aumento no número de dias quentes ao ano, aumento na frequência e intensidade de eventos climáticos extremos, subida do nível do mar, etc.) podem afetar múltiplas funções ecossistêmicas e comprometer a segurança alimentar, saúde pública, economias locais e o sustento de populações de maneiras ainda não completamente compreendidas (Hernández-Delgado, 2015).

O conceito de serviços ecossistêmicos é bastante recente e sua aplicação está começando a se mostrar interessante do ponto de vista de uma abordagem ecossistêmica para os problemas que têm sido observados na zona costeira devido, principalmente, a múltiplos usos conflitantes (Arkema et al., 2015). Tradicionalmente, as iniciativas de gerenciamento da zona costeira têm procurado abordar uma questão por vez, de maneira pouco colaborativa e transdisciplinar (Clarke et al., 2013), mas este cenário apresenta sinais de mudança (Fernandino et al., 2018). Soma-se a essa problemática o fato de os impactos causados por mudanças climáticas ainda serem considerados distantes e, assim, serem tipicamente ignorados na rotina diária de estratégias de manejo costeiro (Ruckelshaus et al., 2013).

O 5º relatório de avaliação do Painel Intergovernamental sobre Mudanças do Clima (IPCC na sigla em inglês) afirma que a taxa de subida do nível médio do mar desde meados do século XIX tem sido maior que a taxa média dos últimos dois milênios (IPCC, 2014). O relatório associa essa informação a um potencial aumento no grau de exposição e vulnerabilidade de populações humanas e ecossistemas. Espera-se, portanto, que serviços ecossistêmicos sejam afetados dentro dos cenários previstos pelo IPCC. No entanto, há ainda poucos estudos que avaliaram os efeitos das mudanças climáticas sobre o fornecimento de serviços ecossistêmicos costeiros (Runting et al., 2017).

Como observado por Elliff e Kikuchi (2017), os recifes de coral do arquipélago de Tinharé-Boipeba, baixo sul da Bahia, fornecem notáveis serviços de provisão, regulação, suporte e cultura. Um achado importante desses autores foi a constatação de que cerca de 50% do litoral das ilhas se tornaria mais vulnerável à erosão e inundação caso os recifes deixassem de fornecer seu serviço de proteção à linha de costa. Os autores ainda enfatizam a preocupação com relação à coincidência de áreas de alto risco de perda de capacidade de fornecimento de serviços e alta vulnerabilidade costeira em um cenário de ausência dos recifes devido ao seu declínio por ações antrópicas locais.

Os efeitos de mudanças climáticas sobre os oceanos já são evidentes e sua tendência é de intensificação nos próximos anos (Ruckelshaus et al., 2013). O aumento do nível do mar é um dos principais problemas associados às mudanças climáticas globais e apresenta diversas implicações para o ambiente costeiro. Fernandino et al. (2018) destacam a submersão e alagamento de zonas costeiras, intrusão de água salgada em águas superficiais e subterrâneas, aumento da erosão costeira, *coastal squeeze*, e perda de ambientes intermareais como alguns dos impactos da subida do nível do mar em diversos locais do planeta.

Apesar de ainda haver incertezas quanto à magnitude do aumento do nível do mar, Nicholls e Cazenave (2010) afirmam que ao longo do século XXI a velocidade dessa subida deverá aumentar. Estes mesmos autores determinaram que o nível do mar na região da costa brasileira sofreu um aumento entre 2-5 mm/ano, incluindo a costa das regiões Norte e Nordeste, com base em dados de altimetria entre 1992 e 2009. No entanto, estes valores foram definidos a partir de avaliações em escala global, carecendo de detalhamento regional e local. Ainda assim, estes valores indicam uma clara tendência de aumento do nível do mar para a costa da região Nordeste do Brasil, justificando a importância de estudos que abordem tal questão e avaliem os possíveis impactos decorrentes desse aumento, permitindo oportunidades de adaptação.

As ilhas de Tinharé e Boipeba, pertencentes ao município de Cairu, estão inseridas na chamada Costa do Dendê, delimitada pelos rios Jequiriçá e Tijuípe (Figura 1). A região apresenta uma linha de costa bastante irregular devido à presença de ilhas, enseadas, canais de maré e recifes em franja, denotando alta geodiversidade. Essa configuração atual e a estruturação da linha de costa da área é resultado da herança geológica local relacionada à inserção da região na Bacia de Camamu, somada aos eventos de regressão e transgressão marinha durante o período Quaternário (Silva et al., 2009).

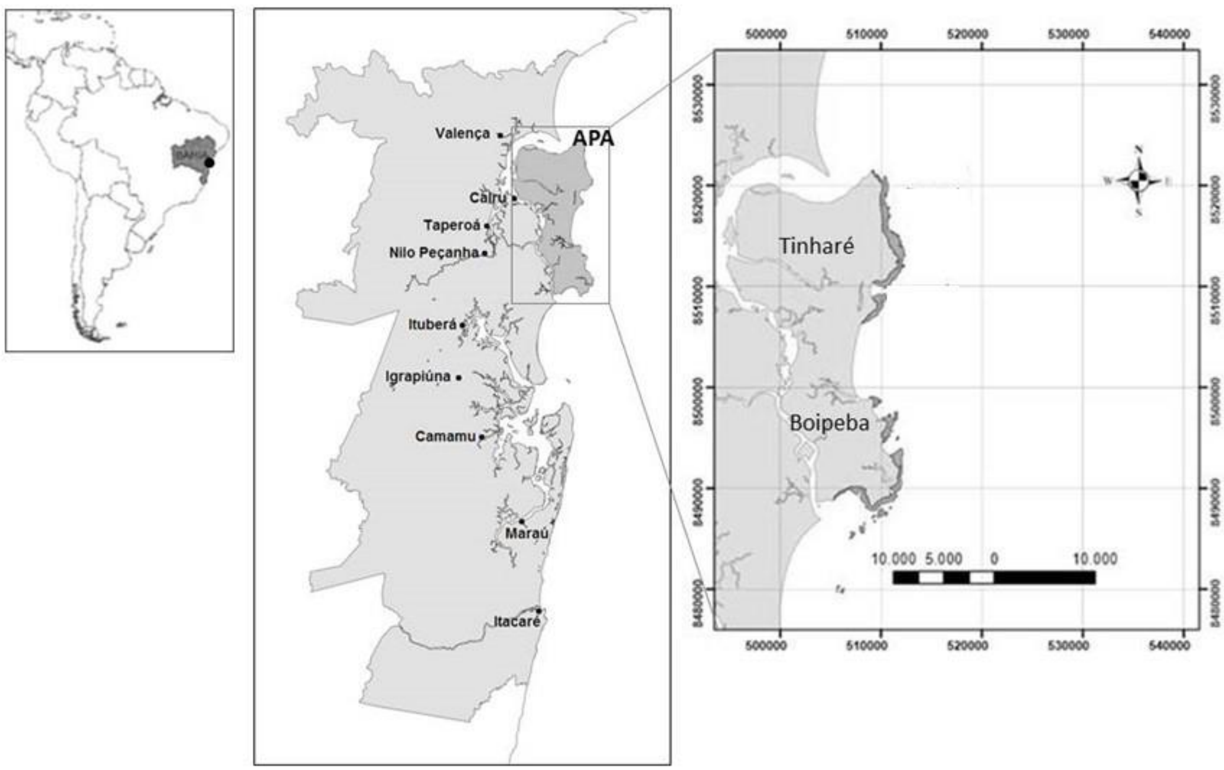

Figura 1. Localização do Arquipélago de Tinharé-Boipeba, Baixo Sul da Bahia, com indicação da ocorrência de recifes de coral em franja bordejando as ilhas (cinza escuro).

O arquipélago está inserido em uma Área de Proteção Ambiental (APA), que constitui uma Unidade de Conservação de uso sustentável. Essa denominação implica que as ilhas podem incluir áreas privadas e públicas, com o intuito de ordenar o processo de ocupação humana, conservar a diversidade biológica local e assegurar a sustentabilidade do uso dos recursos naturais das mesmas. Dentre os atributos naturais da área que são reconhecidamente fundamentais de acordo com o Decreto Nº 1.240 de 05 de junho de 1992 estão os recifes, barras, morros e depósitos costeiros (Brasil, 1992).

Como apontado por Kikuchi et al. (2008), as ilhas de Tinharé e Boipeba apresentam recifes do tipo franjantes aflorantes que bordejam a costa, bancos rasos (entre 5 e 10 m de profundidade), e recifes profundos (entre 10 e 20 m). Recifes aflorantes são caracterizados como aqueles que permanecem emersos durantes as marés baixas de sizígia, englobando assim os recifes em franja e os bancos isolados adjacentes do arquipélago. Ainda de acordo com Kikuchi et al. (2008), devido à evolução costeira quaternária da região, o topo destes recifes tem uma superfície bastante irregular, com o truncamento de antigas colônias e a formação de muitos canais e poças de maré. Além disso, a disposição desses recifes permite a formação de piscinas naturais, que são um grande atrativo turístico na região. A Figura 2 ilustra algumas situações observadas sobre e nos entornos dos recifes de coral do arquipélago.

Dentro de um cenário de mudanças climáticas, há incertezas no que tange a evolução costeira do arquipélago de Tinharé-Boipeba e as implicações dessas alterações para o fornecimento de serviços ecossistêmicos, com ênfase particularmente nos recifes de coral da área.

Apesar da relativa baixa densidade populacional das ilhas, estas são importantes destinos turísticos no estado da Bahia, contribuindo economicamente dentro desse setor. Dada a tendência para um aumento no nível do mar, é de extrema importância investigar como esse efeito poderá afetar os recifes de coral do arquipélago e seu fornecimento de serviços ecossistêmicos.

Figura 2. A) Recifes em franja bordejando a área de Morro de São Paulo, ilha de Tinharé; B) Banhistas abrigados em piscina natural formada pelos recifes; C) Atividade de mariscagem sobre recifes emersos durante a maré baixa, ilha de Boipeba; D) Presença do coral Siderastrea *sp. em poça de maré durante a maré baixa.*

O objetivo geral do presente estudo foi fornecer cenários de mudanças no nível de proteção à linha de costa pelos recifes de coral do Arquipélago de Tinharé-Boipeba baseado em projeções de subida do nível do mar dentro do contexto das mudanças climáticas.

Os objetivos específicos foram:

I. Identificar implicações das mudanças climáticas sobre a vitalidade do ecossistema recifal e sua capacidade de oferecer proteção à linha de costa;
II. Análise do clima de ondas atual e papel dos recifes de coral na atenuação de ondas;

III. Calcular projeções de subida do nível do mar a partir de cenários de mudanças climáticas;
IV. Modelagem do fornecimento de proteção à linha de costa por parte dos recifes de coral diante de subida do nível do mar.

Para atingir os objetivos propostos, foram redigidos três artigos científicos. O primeiro, apresentado no Capítulo 2, foi intitulado "*Coral reefs as the first line of defense: Shoreline protection in face of climate change*" e foi publicado na revista *Marine Environmental Research* (Qualis B1 em Geociências, Fator de Impacto = 3,613) em março de 2017. Este artigo apresenta uma revisão do conhecimento fragmentado na literatura sobre a capacidade de proteção à linha de costa por recifes de coral e os principais impactos decorrentes das mudanças climáticas, atendendo ao objetivo específico I. O segundo artigo, apresentado no Capítulo 3, foi intitulado "*Wave attenuation and shoreline protection by a fringing reef system*" e será publicado no Anuário do Instituto de Geociências da UFRJ (Qualis B1 em Geociências) em seu Volume 42 – 1. Neste estudo são apresentados os resultados de modelagem do cenário atual de clima de ondas para o arquipélago de Tinharé e Boipeba e a influência do sistema recifal da região na atenuação de altura de ondas que chegam à costa, como proposto no objetivo específico II. Por fim, o terceiro artigo, atendendo aos objetivos específicos III e IV, apresentado no Capítulo 4, foi intitulado "*Assessing sea-level rise impacts on coral reef shoreline protection in a data-deficient site*" e será preparado para submissão futura. Neste artigo são apresentados os resultados das modelagens de subida do nível do mar devido a mudanças climáticas e suas implicações para a proteção à linha de costa fornecida por recifes de coral na área de estudo.

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CAPÍTULO 2

ARTIGO 1 – CORAL REEFS AS THE FIRST LINE OF DEFENSE: SHORELINE PROTECTION IN FACE OF CLIMATE CHANGE

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Highlights

• Coral reefs are often associated to shoreline protection by wave attenuation.

• Sea level rise, ocean warming and acidification threaten coral reef resilience.

• Synergies between climate change impacts are still not fully understood.

• Ecosystem service recovery and maintenance rely on ecosystem resilience.

• Shoreline protection becomes more important in face of climate change.

Abstract

Coral reefs are responsible for a wide array of ecosystem services including shoreline protection. However, the processes involved in delivering this particular service have not been fully understood. The objective of the present review was to compile the main results in the literature regarding the study of shoreline protection delivered by coral reefs, identifying the main threats climate change imposes to the service, and discuss mitigation and recovery strategies that can and have been applied to these ecosystems. While different zones of a reef have been associated with different levels of wave energy and wave height attenuation, more information is still needed regarding the capacity of different reef morphologies to deliver shoreline protection. Moreover, the synergy between the main threats imposed by climate change to coral reefs has also not been thoroughly investigated. Recovery strategies are being tested and while there are numerous mitigation options, the challenge remains as to how to implement them and monitor their efficacy.

Keywords: ecosystem services, shoreline protection, climate change, coral reefs, ecosystem management, coastal zone.

1. Introduction

Coral reefs can be considered as relatively rare ecosystems (UNEP-WCMC, 2006). They occupy less than 1% of the global benthic environment, which translates as roughly 250,000 km² of the seafloor (Woodroffe and Webster, 2014; Spalding et al., 2014b). Despite their small proportion, coral reefs are responsible for numerous ecosystem services, which are essential for human well-being and for the way we currently live our lives by the coast.

Ecosystem services can be understood simply as the benefits of natural ecosystems that lead to human well-being (Millennium Ecosystem Assessment, 2005). As reported by Moberg and Folke (1999) and Principe et al. (2012), the most relevant ecosystem services delivered by coral reefs are: i) provision of renewable resources, such as fisheries; ii) services associated with the physical structure of the reef, such as shoreline protection and regulation of erosive processes; iii) biogeochemical services, such as nitrogen fixation and CO_2/Ca control; and iv) information and culture services, such as tourism and leisure opportunities.

In view of the prediction of increasing frequencies and intensities of tropical storms, as well as an increase of mean sea level and other impacts associated with climate change, understanding the importance of coastal environments for the decrease of coastal vulnerability has become essential to address these issues (UNEP-WCMC, 2006).

Thus, the objective of the present review was to compile the main results in the literature regarding the study of shoreline protection delivered by coral reefs, identifying the main threats climate change imposes to the service, and discuss mitigation and recovery strategies that can and have been applied to these ecosystems.

2. Methods

The literature consulted in the present review was selected by first searching for the terms “shoreline protection”, “coral reef”, and “ecosystem services” in academic online search engines. The results of these searches were then sorted according to the objective of compiling the main results in the literature regarding the study of shoreline protection delivered by coral reefs. No geographical or time scale boundaries were imposed. Studies were not considered if their objectives did not include evaluation of shoreline protection by coral reefs. References cited in each relevant article were also consulted to select articles that might have not been found during the first stage of selection. A total of 15 published articles and reports met the criteria established. Further literature was consulted to address the objectives of identifying the main threats climate change imposes to the service, and to discuss mitigation and recovery strategies that can and have been applied to these ecosystems.

3. The ecosystem service of shoreline protection

The fact that coral reefs are able to attenuate incoming wave energy has been known by coastal communities for a long time. There are secular reports of the use of artificial reefs to simulate the services offered by this ecosystem in Japan and India (Moberg and Rönnbäck, 2003). Moreover, areas that are sheltered by reefs and mangroves, for example, have been historically used to establish ports and navigation routes (UNEP-WCMC, 2006).

Despite a wide range of empirical observations, there are few scientific data regarding the capacity for shoreline protection by coral reefs, as reported by the United Nations Environment Program – World Conservation Monitoring Center (UNEP-WCMC, 2006). Studies dating since the 1970s already evaluated the relationship between reefs and attenuation of wave energy. For example, Hayden et al. (1978) mentioned the potential of this service in their study area, though this was not the main focus of their study. Young (1989) also discussed wave attenuation by coral reefs, concluding that a reef structure offered significantly more attenuation than initially expected.

However, Principe et al. (2012) stated that while much progress has been made towards the understanding of wave energy attenuation, there is still the need to connect this attenuation to the supply of ecosystem services. These authors explain that to adequately quantify shoreline protection, studies must investigate the interaction between reef attributes, the physical processes of the marine environment and the relevant benefits delivered to society.

Ferrario et al. (2014) recently addressed some of these issues through a meta-analysis and global synthesis regarding the contribution of coral reefs towards risk reduction along the coast. These authors identified that the first studies specifically regarding this theme were published in the 1990s. However, there is a clear demand for more detailed studies on this subject, considering the relevance of this service in face of climate change scenarios (Spalding et al., 2014a).

A recent study by Arkema et al. (2013) demonstrated the importance of conserving and restoring coastal environments to protect human lives and properties at a national scale in the USA, using an ecosystem-based approach for coastal management. The results of their study indicated that natural habitats currently protect 67% of the coastline, and a loss of these environments would double the extension of areas exposed to storm surges and sea level rise. An interesting observation is that one of the states that benefit the most from coastal protection by natural habitats is Florida, where most of the coral reefs of the USA are concentrated.

At a local scale, Costa et al. (2016) analyzed the influence of reef geometry in the attenuation of waves reaching the metropolitan region of Recife, state of Pernambuco, Brazil. These authors identified that reefs located on the continental shelf (>2 m depth) were able to reduce up to 67% of wave energy, while fringing reefs reduced up to 99.9% of this energy during low tides.

Mallmann and Pereira (2014), also in the state of Pernambuco, Brazil, suggested that a solution/mitigation option for the coastal erosion observed in the studied area would be the construction of submerged breakwaters, which simulate a natural reef. The authors explain that this type of structure would reduce offshore sediment transport by rip currents and loss of sediment to the continental shelf, slowly promoting beach recovery.

However, the response of shoreline protection by coral reefs in extreme hydrodynamic conditions may vary. As presented by UNEP-WCMC (2006), while reefs are important for shoreline protection under normal conditions and even during hurricanes and tropical storms, in the case of tsunamis their capacity is more variable.

The form, structure and force of a tsunami differ greatly from that of normal waves. Thus, the buffering capacity of reefs is likely to be reduced.

3.1 Mechanisms for delivering the service of shoreline protection

As described by Quataert et al. (2015), in addition to the presence or absence of the reef, attributes such as reef dimensions, topography and rugosity should also be considered to understand in detail the processes of wave height and wave energy attenuation (Figure 1).

Coral reefs are able to reduce the energy of offshore waves by causing wave break over the reef crest and causing friction due to the rugosity of the reef flat (Principe et al., 2012). All these attributes vary greatly from one reef to another and can present different levels of interaction. For example, wider reef flats are associated with greater wave energy and wave height attenuation rates (UNEP-WCMC, 2006). As described by Quataert et al. (2015), reef flat width is expected to affect energy dissipation rates due to friction along the reef. However, narrow flats also promote significant attenuation, given that 50% of the energy attenuation that occurs over reef flats occurs along the first 150 m of this zone (Ferrario et al., 2014).

Ferrario et al. (2014) identified that, globally, reefs are able to attenuate in average 97% of incoming wave energy, as well as reducing in average 84% of the height of these waves. Regarding the different zones of the reef, these authors identified that the crest is responsible for decreasing in average 86% of wave energy and 64% of wave height, while the reef flat decreases in average 65% of wave energy and 43% of wave height.

In addition to the different zones of a coral reef, the morphology of the reef itself should also be considered when evaluating its capacity to attenuate energy. The literature still lacks studies that compare the capacity of delivering shoreline protection by different types of reefs (i.e. fringing reefs, barrier reefs, reef patches, atolls, among others). However, considering that wave runup usually increases in conditions where there is a narrower reef flat, steeper forereefs, lower reef flat friction, and greater friction at the forereef (Quataert et al., 2015), hypotheses can be elaborated for specific cases. It is important to keep in mind that coral reefs are highly dynamic biophysical systems, which undergo constant physical, chemical and biological changes (Hayden et al., 1978). Moreover, evaluating the goods and services delivered by coral reefs is not an easy task, given the complexity and variety of this ecosystem (Moberg and Folke, 1999).

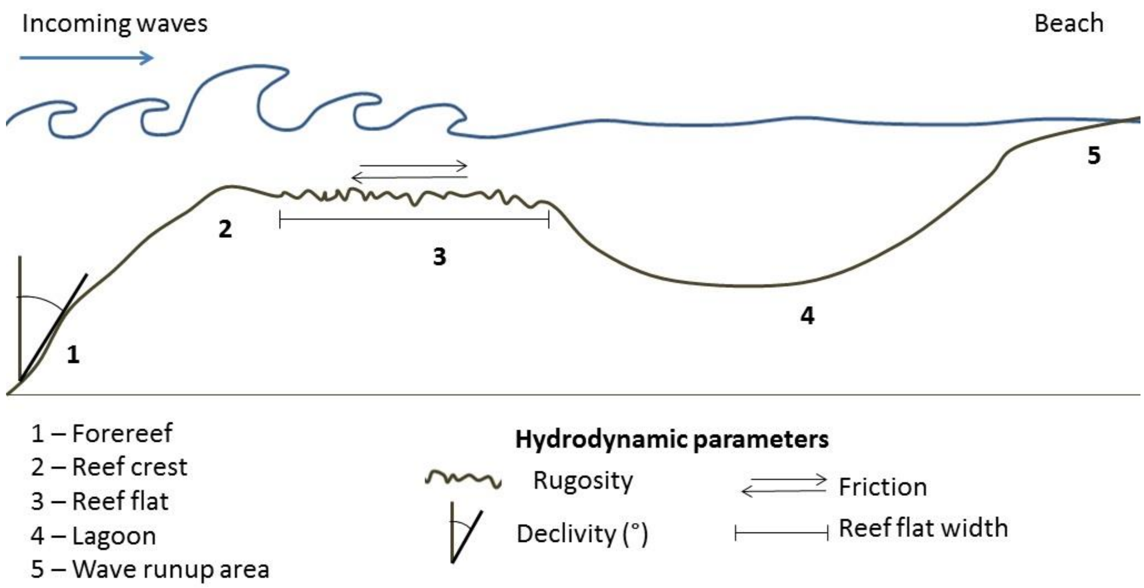

Figure 1: Reef zones and hydrodynamic parameters involved in the process of wave height and wave energy attenuation.

4. Threats to the service of shoreline protection

Similar to other ecosystems, the ability of a coral reef to deliver ecosystem services depends intrinsically on their resilience condition (Elliff and Kikuchi, 2015). Thus, degraded reefs or reefs that are under stressful conditions have a reduced capacity to deliver their numerous services, including shoreline protection. Reefs under favorable conditions and without negative human impacts act as self-repairing breakwaters, balancing growth with the erosion caused by incoming waves, storm surges and other coastal processes (UNEP-WCMC, 2006).

Moberg and Folke (1999) reported that the recovery of reefs in face of persistent human impacts (i.e. pollution, sediment inputs) is slower than in face of natural impacts (i.e. hurricanes, predator outbreaks). However, more recent studies highlight concern particularly over the synergy of cumulative impacts caused by climate change (Hernández-Delgado, 2015).

The 5th report of the Intergovernmental Panel on Climate Change (IPCC) explains that high levels of human greenhouse gas emissions have led to unprecedented atmospheric concentrations. The most recent results of research carried out in the field of climate science allowed the conclusion that it is extremely probable that this increase in carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) combined to other anthropic factors, such as alterations in land use and land occupation patterns are the dominant cause for global warming observed since the mid-20th century (IPCC, 2014).

Increases in ocean temperature and ocean acidification are considered the two most relevant impacts to coral reefs among the phenomena associated with climate change (Ateweberhan et al., 2013). However, consequent variations in mean sea level also cause important alterations to reefs, such as time emerged during low tides, hydrodynamics and light availability for the benthos (Saunders et al., 2015).

4.1 Increases in ocean temperature

Coral reefs are sensitive ecosystems. The optimum growth interval of a reef occurs in conditions between 23 °C and 29 °C, though currently most corals live in conditions near their maximum thermal intervals (Spalding and Brown, 2015). This narrow thermal interval is mostly due to the zooxanthellae, which are microalgae of the *Symbiodinium* genus that live in symbiosis with reef building corals, supplying most of the necessary energy for these organisms (Wild et al., 2011). This symbiotic relationship is broken in stressful situations, such as an increase in temperature above that which is tolerated. In this case, the zooxanthellae are expelled from the coral tissue, leaving the host without its main source of energy and with a pale or even white color, characterizing the process known as coral bleaching (Pandolfi et al., 2011).

Coral bleaching due to the loss of symbiotic algae is a reversible process, but leaves the coral physiologically compromised (Wild et al., 2011). Thus, corals become susceptible to disease, the carbonate structure of the reef weakens due to reduced calcification, coral reproduction can be compromised, and there can be increased mortality rates (Spalding and Brown, 2015). All this can, in turn, lead to lower rugosity of the reef and cause lower wave energy dissipation.

Although reef organisms from shallow tropical waters have existed in atmospheric conditions of CO_2 up to 20 times those observed in pre-industrial times, the reaction of coral reefs in face of current conditions of increased CO_2 concentrations cannot be predicted from the fossil record, since there are no records of such a rapid increase (Pandolfi et al., 2011). Thus, the main concern is that the current community of reef building corals is not able to acclimate to these conditions of such an abrupt temperature increase.

4.2 Ocean acidification

Another consequence of an increase in greenhouse gas emissions is ocean acidification. With an increase in atmospheric CO_2 concentration and subsequent absorption by the oceans, there is a decrease in ocean pH, causing a decrease in the saturation state of aragonite, an essential element for coral skeletons (Pandolfi et al., 2011).

Wild et al. (2011) warn that this decrease in coral skeleton formation leads to a decline in the ability to build reefs, thus compromising the development and maintenance of indispensable reef environments. Again, the compromised reef structures can become more flattened and lower wave energy dissipation.

As is the case with increased ocean temperatures, although reef communities were present in past conditions of higher CO_2 than those observed currently, these are not compatible with contemporary conditions due to the time scale considered (Pandolfi et al., 2011).

4.3 Mean sea level rises

The 5th IPCC report indicates that the rate of mean sea level rise since the mid-19th century has been greater than the mean rate of the past two millennia (IPCC, 2014). Moreover, Nicholls and Cazenave (2010) affirm that throughout the 21st century the velocity of this rise will increase. However, studies must take into consideration that there are different trends of sea level variation across the globe, which are associated with climatic and non-climatic factors. Climatic factors regard climate change, observed through phenomena such as the melting of icecaps and thermal expansion of seawater. Non-climatic factors regard phenomena such as subsidence and uplifting, as well as human actions such as the building of dams that interrupt sediment input to a coastal environment, for example, intensifying erosion and causing a retreat of the coastline towards the continent (Nicholls and Cazenave, 2010).

As previously discussed, sea level variations can affect the vitality of coral reefs (Saunder et al., 2015). An increase in sea level can lead a reef to three different evolution categories: a keep-up reef, a catch-up reef or a give-up reef (Figure 2). According to this classification by Neumann and Macintyre (1985), a keep-up reef presents a growth rate equivalent to the rate of sea level rise; a catch-up reef initially presents a lower growth rate than the sea level rise, but later reaches the stabilized mean sea level with a more accelerated growth; and a give-up reef is not able to follow the rate of sea level rise, presenting low growth rates that eventually stop. These three alternatives illustrate well how reef vitality can have an important role on the geological evolution of these carbonate structures. A reef that is undergoing negative impacts and has low vitality indices will not have the same resilience and, therefore, adaptation capacity as a reef in better conditions of integrity. However, some reefs are naturally bound to the characteristics of a give-up reef, such as low growth rates, so their geological evolution may not depend on their resilience.

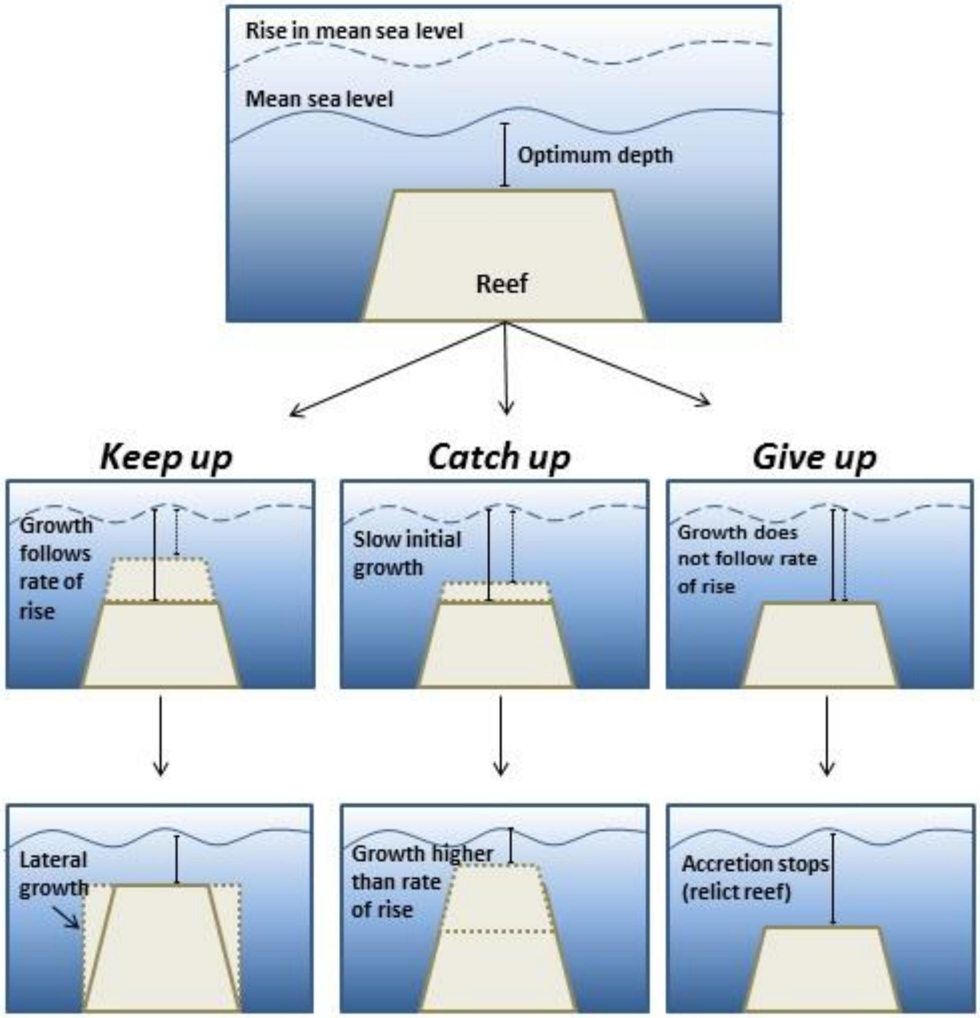

Figure 2: Schematic representation of the classification of Neumann and Macintyre (1985) for the growth processes of coral reefs in face of a mean sea level rise. Keep-up reefs present growth rates that follow the rates of the rising sea level, allowing lateral growth once the mean sea level reaches stability. Catch-up reefs present an initially slow growth, but later their rates of growth reach the stabilized mean sea level. Give-up reefs have very slow growth rates and are not able to follow the rate of mean sea level rise, becoming relict reefs when accretion stops.

4.4 Synergy between impacts and their influence on the service of shoreline protection

In the natural environment there is no way to clearly separate all the diversity of ecosystem processes without overlapping each other. However, potential interactions and the synergy between various negative impacts (either associated with climate change or not) and coastal ecosystems are still not fully understood (Hernández-Delgado, 2015). Thus, while the processes of ocean warming, ocean acidification and mean sea level variations have been clearly linked respectively to coral bleaching, reduced rates of reef growth and different scenarios of reef growth and decline, as previously described, these phenomena still need to be analyzed in an integrated manner regarding their impacts on the supply of essential ecosystem services.

One of the most relevant threats to the ability of coral reefs to deliver ecosystem services lies on the degradation of the reef structure. Graham and Nash (2013) reported that there has been an expressive increase over the past four decades in the study of the role of reef complexity for the ecosystem, thus demonstrating the importance of this single parameter. However, these same authors discuss that due to a lack of standardization among studies, small scale and empirical nature of investigations, not all roles played by structural complexity could be detailed for the reef ecosystem.

As previously discussed, among the harmful effects of coral bleaching and ocean acidification is the decline in growth rates of the reef and weakening of its structure. Thus, the reef becomes more susceptible to erosion by abiotic factors and also bioerosion. Although these processes are part of the natural balance of a coral reef, bioerosion in particular is estimated to accelerate in scenarios of ocean acidification, temperature extremes, and occurrence of diseases, among other stressful factors (Glynn and Manzello, 2015).

Quataert et al. (2015) alert that bleaching events and ocean acidification, either acting separately or together, are likely to reduce to friction effect promoted by the rugosity of the reef, which could lead to an increase in wave height, wave runup and coastal flooding. Ferrario et al. (2014) also identified rugosity as one of the most relevant parameters for wave energy attenuation and affirmed that reef degradation significantly impacts this aspect.

With the death of reef building corals, the area can become occupied by non-reef-building organisms, such as macroalgae or zoanthids, characterizing a process known as phase shift. The dominance of macroalgae in place of reef building coral compromises the supply of services associated with the three-dimensional reef structure (Wild et al., 2011). This change of seascape can be considered as just a disturbance in an evolution scale, but, at a human scale, this change can seriously compromise the benefits acquired through ecosystem services (Moberg and Folke, 1999). Spalding and Brown (2015) mention the occurrence of this phenomenon after the huge bleaching event of 1998, which was a consequence of a very intense El Niño. If the reef is not able to recover from this phase shift, the reef structure will inevitably undergo flattening as a consequence of the natural erosion of these environments, compromising wave height and wave energy attenuation processes.

The ecosystem service of shoreline protection can also be greatly hindered in a scenario in which the growth rates of a reef are below the projections for mean sea level rise. A reef with low resilience, in other words, suffering cumulative and synergetic impacts from negative natural and human induced impacts, will be less likely to adapt. In this case, the reef could possibly become a give-up reef, since it would be below the optimum photic zone for supplying the energetic needs of the corals and accretion would stop. Another important aspect is that throughout this process of mean sea level rise, the reef would become deeper and, thus, would also lose its capacity to attenuate incoming wave energy since it would no longer be located at the ideal depth to do so (Principe et al., 2012).

However, new colonization areas can also be produced with the flooding of stable substrates and with an increase in the water column over intertidal reef plateaus. Saunders et al. (2015) reported that a sea level rise can stimulate the growth of reefs that were spatially limited previously. These authors describe that this growth can occur by means of lateral expansion, fragmentation of existing colonies (vegetative reproduction), larval settling, recruitment and growth of new colonies, resulting in both vertical and horizontal increases in coral cover. However, this alternative scenario in which the reef experiences growth instead of decline will depend on ecosystem integrity, resilience condition, and reproductive and colonization capacity of the species that compose the reef.

5. Recovering the ecosystem service of shoreline protection

Considering the value of the benefits obtained from coral reefs, conservation strategies towards these ecosystems represent a relatively low investment with a high return (White et al., 2000; Ferrario et al., 2014).

Reefs are usually able to recover from a stressful event when there is an adequate supply of coral, fish and invertebrate larvae, and as long as chronic disturbances such as sedimentation, pollution and overfishing are minimized (UNEP-

WCMC, 2006). Moberg and Rönnbäck (2003) alert that many recovery actions are still at a trial-and-error stage and depend largely on the existence of healthy fish and flora assemblages to recolonize the damaged area.

The recolonization of coral species over degraded reefs offers an opportunity to reduce the risk of phase shifts in these areas, as explained by Hoegh-Guldberg et al. (2007). However, these authors state that there are many uncertainties regarding the methods to increase rugosity and live coral coverage over reefs, as well as a disagreement between the practical scale for restoration by means of recolonization (hectares) and the extension of degraded areas (thousands of km²).

Another option that has been widely explored is the use of artificial reefs not only to simulate declining ecosystem services, but also to stimulate the settling of larvae and biomass production (Castanhari et al., 2012). Ido and Shimrit (2015) described the implementation of a system of concrete structures using an ecosystem-based management approach, which was considered more beneficial, to address this issue. In their study, the authors used concrete blocks with an “eco-design” to form a submerged breakwater to mitigate erosion in a coastal area in Israel. After two years, this structure presented a highly rich and diverse live cover, while the complex texturized surface of the structure remained intact, with no signs of weathering. The biogenic accretion of building species (oysters, mussels and barnacles) considerably increased the support capacity of the structure for rich benthic communities.

6. Maintaining the ecosystem service of shoreline protection

Ecosystem service maintenance depends on strategies to adequate human activities within the resilience and carrying capacity limits of each ecosystem. As discussed by Elliff and Kikuchi (2015), the coastal zone requires immediate action regarding local impacts, such as pollution, overfishing and other forms of environmental degradation, to be able to face the challenges of lack of monitoring and of information, as well as conflicts between users, within an integrated coastal zone management framework. A wide range of guidelines, conduct codes and information are already available regarding how to efficiently manage an area with coral reefs, but there is a remarkable lack of commitment to apply these strategies (UNEP-WCMC, 2006).

Among the possible tools that can aid in the recovery of coral reef resilience is the definition of more restrictive environmental protection areas. However, Ban et al. (2011) pondered that while there is much information already available regarding the use of marine protected areas for coral reef management, these recommendations and trends have still not been adequately synthesized considering the context of developing nations, where most of the world's coral reefs are located.

Another tool applied in several environmental parks and reserves is charging a fee for maintaining the area. Payment for ecosystem services can be an interesting tool, as long as the revenue gathered is applied towards conservation projects to allow ecosystems to continue to deliver their services efficiently (Ruckelshaus et al., 2013). Farr et al. (2011) described in their study the experience of charging an entry fee to the Great Barrier Reef in Australia and indicated that this strategy could be interesting especially for countries that have difficulty in gathering funds for preserving their protected areas.

It would be naïve to try to maintain any ecosystem in pre-Anthropocene levels of quality, but it is also too soon to declare the end of coral reefs (Spalding and Brown, 2015). As previously mentioned, coral reefs are extremely sensitive ecosystems, but they have been found in fossil record to exist in very high CO_2 conditions in the past. Pandolfi et al. (2011) list five episodes of serious coral reef biodiversity loss or interruptions to reef growth at a global scale, which became known as the reef crises. However, the authors also make it clear that these episodes occurred over a geological scale.

7. Conclusions

The main concern regarding the impacts of climate change over coral reef ecosystems resides in the issue of the velocity of these changes, which does not allow the acclimation of several species. Without the possibility to adapt, the scenario that is imposed is that of a decline of several ecosystems and the services they deliver.

Reef morphology still needs to be better understood to address shoreline protection from the whole diversity of reef systems. Moreover, the synergy of impacts to reef ecosystems also requires more detailed studies. With this information, efficient recovery and management strategies can be developed.

Shoreline protection has gained the spotlight in recent investigations because of its potential to attenuate the effects of climate change in coastal areas. However, one of the most relevant ecosystems in the delivery of this service is precisely one of the most sensitive to climate change impacts: coral reefs.

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CAPÍTULO 3

ARTIGO 2 – WAVE ATTENUATION AND SHORELINE PROTECTION BY A FRINGING REEF SYSTEM

Atenuação de ondas e proteção à linha de costa por um sistema de recife em franja

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Resumo

Conhecimento sobre dinâmica costeira é essencial para tomadas de decisão baseadas em evidências, no entanto esse tipo de informação ainda é escasso, particularmente em áreas com recifes de coral e outros ecossistemas complexos. O objetivo deste estudo foi contribuir para o entendimento de atenuação de ondas e proteção costeira em momentos distintos por um sistema de recife em franja em um arquipélago do Atlântico Sudoeste. As direções predominantes de ondas offshore foram ESE, SE, E and SSE. Os recifes de coral mostraram alta eficiência em reduzir a altura de ondas incidentes mesmo em condições energéticas durante marés altas. Focos de erosão ao longo do arquipélago foram associadas a correntes de retorno, que eram muito débeis ou até ausentes durante as marés baixas. A conservação dos recifes de coral é essencial para manter a proteção à linha de costa e informação sobre a geomorfologia dos recifes deveria ser incluída em protocolos de monitoramento.

Palavras-chave: clima de ondas, recifes de coral, atenuação de ondas, SMC-Brasil

Abstract

While knowledge on coastal dynamics is essential to guarantee well-informed decision making, information is still scarce, particularly regarding areas with the presence of coral reefs and other complex ecosystems. The objective of the present study was to contribute towards the understanding of wave attenuation and shoreline protection at different tide moments by a fringing reef system located in a Southwestern Atlantic archipelago. The predominant directions of offshore waves adjacent to the archipelago were ESE, SE, E and SSE. Coral reefs demonstrated high efficiency in wave height attenuation even under higher energy conditions during high tides. Erosion hot-spots along the archipelago were associated with rip currents, which were greatly reduced or absent during low tides. Coral reef conservation is essential to maintain shoreline protection and information on reef geomorphology should be included in reef status protocols to help advance this field of knowledge.

Keywords: wave climate, coral reefs, wave attenuation, SMC-Brasil

1 Introduction

The coastal zone is a highly dynamic environment molded by the action of waves, tides, winds, and also sediment grain size, beach slope, storm surges, presence of geologic features, among others. Coral reefs are an example of a geologic feature that can affect incoming waves and are frequently responsible for the ecosystem service of shoreline protection. However, current literature still lacks comparisons on the capacity of wave energy and wave height attenuation by different reef morphologies (Elliff & Silva, 2017). As indicated by Quataert et al. (2015), while some correlations can be made between different morphologies, the biological community, geology and hydrodynamic conditions are extremely variable.

Beaches fronted by coral reefs commonly present more complex topography, which results in wave transformation processes that are also complex, making the role of reef systems unclear regarding coastal morphology (Costa et al., 2016). Moreover, as stated by Monismith (2007), since the geometry of reef systems are unlike those of beaches, for example, which are more commonly studied ecosystems, investigations on coral reefs are expected to generate novel insights on coastal dynamics from a more general perspective. Thus, to ensure a reliable assessment of the potential of shoreline protection provided by coral reefs, local studies are necessary especially within an ecosystem-based management framework.

However, high-quality long-term data for coastal dynamics characterization are not always available. In fact, decision-makers and stakeholders of most coastal zones of the world have difficulties in proposing adequate management strategies due to lack of local information (Fernandino et al., 2018a). Moreover, with most coral reefs located in developing nations, the study of this ecosystem can become more difficult due to socioeconomic challenges. Thus, the objective of the present study was to contribute towards the understanding of wave attenuation and shoreline protection at different tide moments by a fringing reef system.

2 Materials and methods

2.1 Study area

The coastal Archipelago of Tinharé-Boipeba was used as a case study to better understand the role of the existing fringing reef system in coastal dynamics and shoreline protection. This Southwestern Atlantic archipelago is located in the state of Bahia, Brazil, along a stretch of coastline known as Costa do Dendê (Figure 1). The archipelago is inserted within a mosaic of environmental protected areas and is classified as a sustainable use conservation unit.

However, with increasing pressure from the growing tourism industry and poor coastal management, the archipelago experiences several environmental conflicts, such as the presence of oil residue on beaches, marine litter, decline of coral reefs and coastal erosion. Silva et al. (2009) evaluated the environmental sensitivity of the beaches of the archipelago towards coastal erosion and identified that most of the shoreline of both Tinharé and Boipeba islands are highly sensitive to erosion, a concerning situation for a community that deeply relies on coastal tourism for revenue. Dominguez & Corrêa-Gomes (2011) also identified important erosion hot-spots, particularly in the most populated areas of the islands.

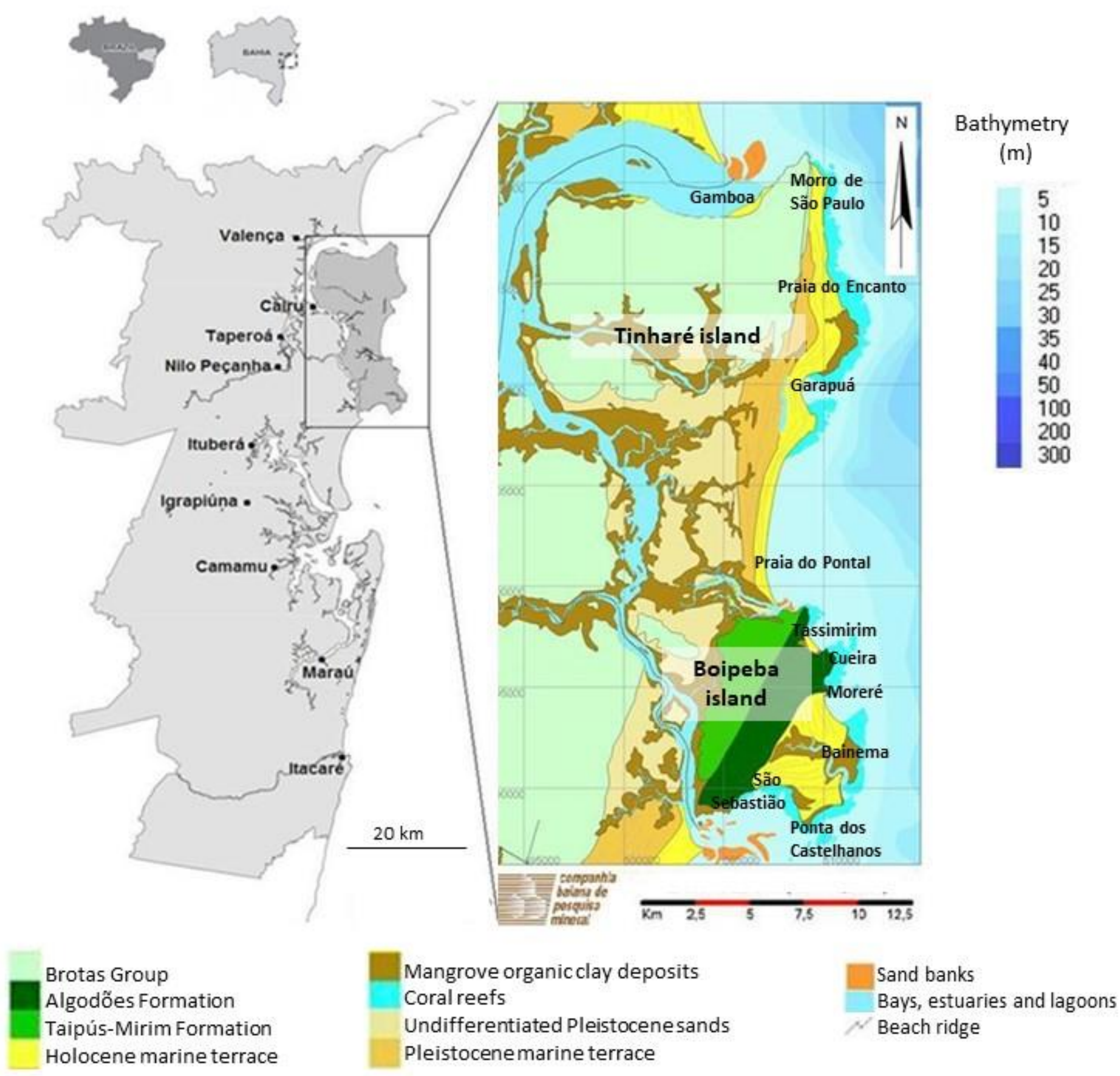

Figure 1 Location and geology of the Archipelago of Tinharé-Boipeba (modified from Dominguez & Corrêa-Gomes (2011)). Located on the coast of the state of Bahia, the municipality

of Cairu encompasses this coastal archipelago. The islands contain high geodiversity and are located on the narrowest part of the Brazilian continental shelf. Fringing coral reefs border most of the two largest islands, Tinharé and Boipeba. This coastal area is an important tourist destination, with the main visited sandy beaches named on the right.

The coastline of the whole region in which the archipelago of Tinharé-Boipeba is inserted is highly indented. Silva et al. (2009) explain that the current configuration of the region is related to the geological inheritance of the Camamu Basin, through the Mesozoic sedimentary rocks of the area, and to the marine regression and transgression events that occurred during the Quaternary, which formed Holocene and Pleistocene marine terraces. Cliffs, which measure between 5 and 80 m in height, are formed by the outcropping of sandstones and limestones of the Camamu Basin itself and are mostly undergoing a retreat process, leading to the formation of small coves and pocket beaches (Silva et al., 2009). Marine regression and transgression events also defined the archipelago's characteristically truncated coral reef tops, which were formed during the last of these regression events and led to the formation of channels and tide pools.

Although the coral reefs of the Camamu Bay, which encompasses the Archipelago of Tinharé-Boipeba, were the first Brazilian coral reefs to be reported in the literature, the region remains one of the least studied areas in the state of Bahia (Leão et al., 2003). The coral reefs of the Archipelago of Tinharé-Boipeba are mainly fringing reefs that border the shoreline, with occasional shallow banks and deeper reef banks. The fringing reefs and the adjacent isolated banks are found emerged during low tides, forming natural pools (Elliff & Kikuchi, 2017).

2.2 Coastal dynamics

Almeida *et al.* (2015) detail how the scarcity of coastal hydrodynamic data has led to the creation of models that can meet this demand, particularly in Brazil with the Brazilian Coastal Modeling System, SMC-Brasil (Sistema de Modelagem Costeira – Brasil). In the present study, coastal dynamics were modelled using SMC-Brasil, which comprises a suite of software and methodologies. As presented by González et al. (2016), this free system is the product of a partnership between the Brazilian Ministry for the Environment and the Environmental Hydraulics Institute of the Universidad de Cantabria (IHCantabria), Spain, which sought to provide Brazilian researchers and environmental planners with an instrument to improve coastal zone management, including in face of climate change. SMC-Brasil includes a database for marine hydrodynamics (waves, sea level, bathymetry and coastline) that allows behavioral reanalyses of waves and tides over a 60-year period (1948-2008), with temporal resolution of one hour and grid of 1 km² (González et al., 2016).

SMC-Brasil methodology consists on selecting a series of representative cases from the available data on wave climate and propagate the cases from deep water to the point of interest near the coast by means of the maximum dissimilarity (MaxDiss) technique (Camus et al., 2011). A detailed description of the tool's framework and functionality can be found in the user's manual, available at <http://smcbrasil.ihcantabria.com/downloads/>.

2.3 Bathymetry

The bathymetry available for the study area in the SMC-Brasil database is a digitized version of Nautical Chart No. 1100 of the Brazilian Navy. To improve resolution, the bathymetric shapefile available from the study conducted by Dominguez & Corrêa-Gomes (2011) was added and bathymetry was also manually corrected to consider the presence and morphology of all major reef banks and fringing reef structures along the studied area. To do so, aerial images from Google Earth Pro were used combined with the coral reef shapefile also made available by Dominguez & Corrêa-Gomes (2011). Mean depth of 0.5 m was attributed to all reefs that are found to be emerged during low tides.

2.4 Wave climate analysis

The SMC-Brasil wave database was composed following three steps. The first regarded a global reanalysis, called Global Ocean Waves (GOW), which was carried out for the C3A project (Project on Coastal Climate Change Impacts in Latin America and the Caribbean) of the United Nations Economic Commission for Latin America and the Caribbean (CEPAL). The second step was to perform the downscaling of the GOW data for the Brazilian coast. This was carried out by applying the Simulating Waves Nearshore (SWAN) model, adding more detailed bathymetry (nautical charts) and regional wind data. The reconstructed wave series generated through this methodology were named Downscaled Ocean Waves (DOW) (Camus et al., 2013). These two steps are embedded within the SMC-Brasil framework, but to apply them to a given study area, they must be transferred to the coast with greater spatial resolution.

Step three of this methodology regards this aspect and is case-specific, since wave transference is greatly influenced by the local characteristics of each area, particularly bathymetry (Camus et al., 2013). As described by Almeida et al. (2015), for this analysis of wave climate in a given study area, a DOW point located preferably beyond the continental shelf should be selected. The wave climate characteristics of this DOW point analysis are used to create a set of representative cases of mean and more energetic conditions. The parameters of each case were wave height (Hs), peak period (Tp), mean direction (θm), peak enhancement factor (γ), and angular dispersion (σ). Based on these values, the cases were then used to establish grids for the transference of wave propagation to the shoreline, according to the most frequent wave directions observed. Wave propagation was conducted through the OLUCA-SP model, which is included within the SMC-Brasil framework. As described by González et al. (2007), OLUCA-SP is a weakly nonlinear model that combines refraction and diffraction, including the effect of shoaling, energy dissipation through bottom friction and wave breaking, and interactions between waves and currents. Cases were modelled in each grid designed for mean and more energetic conditions, considering low, mean and high tide values, to obtain coastal wave climate and wave-induced current patterns.

3 Results

3.1 Wave climate of the selected DOW point

The predominant directions of offshore waves adjacent to the Archipelago of Tinharé-Boipeba were, in decreasing order, ESE, SE, E and SSE. Most waves originated from ESE (60.11%), but the most energetic sea conditions, represented by the highest values of Hs12 and Tp12 were recorded for waves originating from SSE, which are associated with cold fronts reaching the area. The months of December, January and February (austral summer) presented the greatest occurrence of waves with lower heights, while the months of June, July and August (austral winter) showed higher occurrence of larger waves.

The combined distribution of wave height and peak period (Hs-Tp) analysis showed that the mean and most frequent waves occurring in the offshore area adjacent to the archipelago measure between 1.1 m and 1.8 m and have peak periods between 6 s and 8 s. Moreover, the return period was also calculated for the offshore waves to account for episodic events. While the most probable energetic Hs12 value observed was 3.25 m, there is a chance that every 10 years the area will experience waves with up to 3.5 m in height, and that once every 25 years there could be waves measuring up to 3.8 m.

3.2 Wave climate on the coast

Wave climate during mean conditions and extreme conditions was similar along the coastline, with the main difference being the height and period of incoming waves. Waves from a general eastward direction suffer little diffraction along the reefs, reaching the shoreline at an almost perpendicular angle due to refraction. The coral reefs at the southernmost portion of the island of Boipeba create a protected area adjacent to São Sebastião in these conditions.

When considering waves originating from a general SE direction, the scenario changes. The southernmost area of Boipeba, that was protected from waves incoming from E, became more affected. The coral reefs in this area cause diffraction and waves reach the shoreline at an angle, leading to longshore drift. However, in this scenario, other areas become sheltered from incoming waves due to the presence of coral reefs, such as Garapuá and Moreré. Waves suffer diffraction also across the long open sandy beach stretch in the center-southern portion of Tinharé and reach the coast perpendicularly.

Wave heights reaching the shoreline were affected both by the conditions of these waves (mean or more energetic) and by the tide. As expected, waves in storm surge conditions are larger and can reach the shoreline with more energy. However, the fringing reefs bordering the archipelago form a natural storm barrier and, as the first obstacle to encounter the waves, lead to the attenuation of both wave energy and wave height. The ability to provide this ecosystem service varied according to the tide: during low tides the top of these reefs are emerged and completely block incoming waves, while during high tides reefs are less able to attenuate wave energy and height since they are completely submerged. However, even in more energetic conditions during high tides, the coral reefs of the Archipelago of Tinharé-Boipeba were able to decrease wave height from over 2.5 m to under 0.5 m (Figure 2).

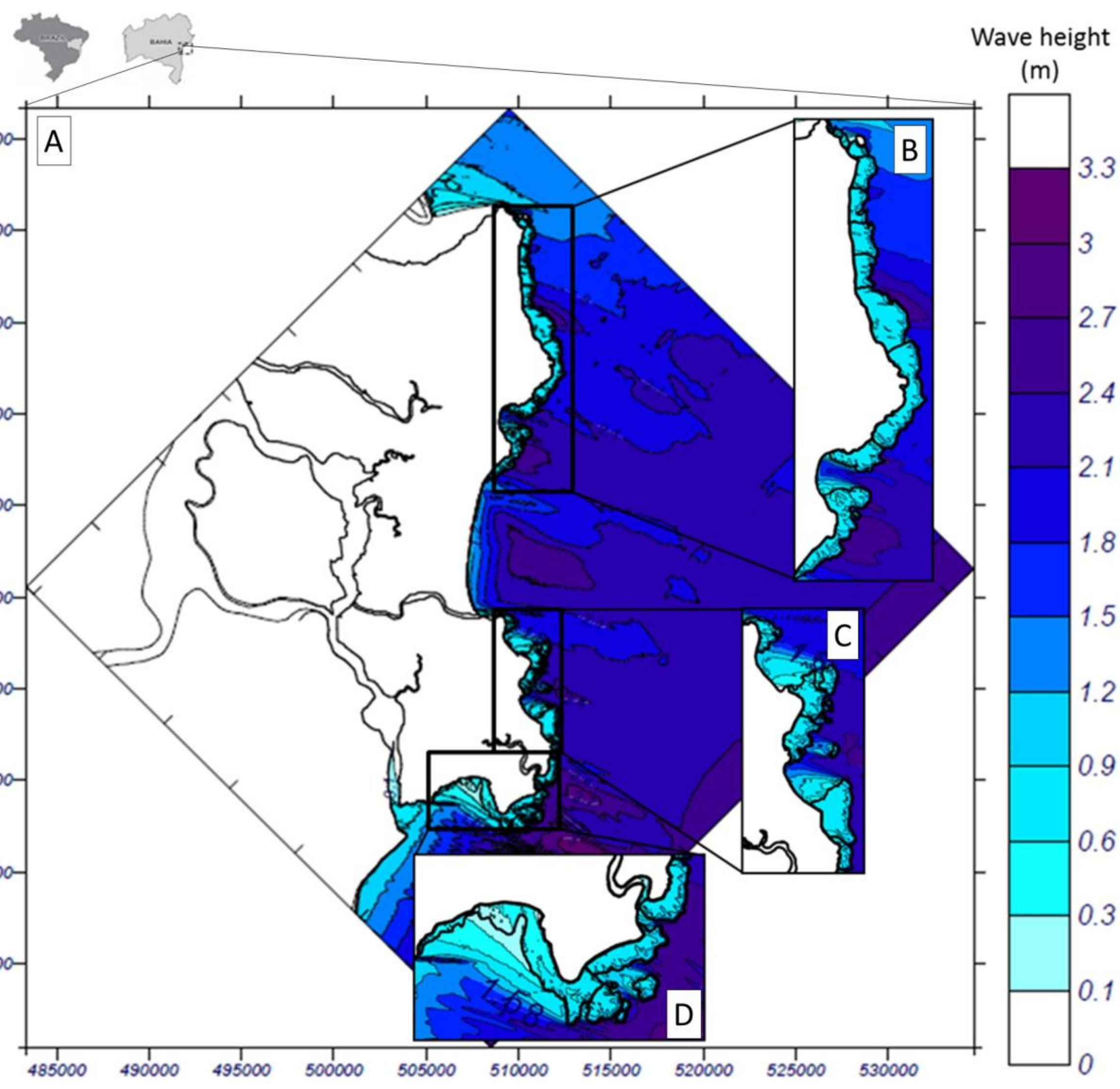

Figure 2 A. Overview of wave heights in more energetic conditions during a high tide in the Archipelago of Tinharé-Boipeba, in which coral reefs (black outline adjacent to the shoreline)

promote a considerable reduction; B. Fringing coral reefs extending from the densely populated area of Morro de São Paulo until the cove of Garapuá efficiently decreasing wave height; C. The northern portion of the island of Boipeba, where most inhabitants of this island are located, is protected directly by fringing and patch coral reefs and indirectly by the shadow zones they create; D. The southernmost area of the archipelago also presents an important shadow zone created by the attenuation of wave height by the coral reefs.

Wave induced coastal currents were found to be stronger over areas occupied by the reefs, since wave breaking occurred in this region. Rip currents were observed particularly in areas where coral reefs were present around but not directly in front of the beach, such as in Garapuá and Moreré. However, this phenomenon was either not observed or was less significant during low tides. Currents during mean tide levels reached greater velocities when compared to high and low tides within the same case analyzed. Moreover, the strongest currents were caused by southeastern waves during storm surge conditions.

4 Discussion

The presence of a fringing reef system along the Archipelago of Tinharé-Boipeba had an important influence on the coastal dynamic processes analyzed in the area. Coral reefs were particularly relevant regarding wave height attenuation to the shoreline. Despite a broad range of empiric observations, there are still few direct scientific data regarding effective shoreline protection by coral reefs, as indicated by Reguero et al. (2018).

Costa et al. (2016) analyzed the influence of reef geometry in wave attenuation at another Brazilian reef. These authors identified that reefs located on the continental shelf could reduce up to 67% of incoming wave energy, while fringing reefs reduced up to 99.9% during low tides. Although wave attenuation was not analyzed in a quantitative manner in the present study, the results of Costa et al. (2016) agree with the present findings, which showed high efficiency of wave height attenuation by fringing reefs, even under more energetic conditions.

An important reef attribute for wave energy dissipation is friction over the reef flat (Quataert et al., 2015). While SMC-Brasil does consider friction in general, the model is not prepared to evaluate friction at the level of reef rugosity. In fact, as indicated by Hearn (2011), important developments in the field of reef hydrodynamics modelling considering measured roughness maps should become available over this decade. Thus, a more thorough quantitative analysis of shoreline protection in the area could build on the results of the present study and add information regarding reef rugosity and detailed geometry as new technologies become available for this and other study areas.

Lack of interdisciplinarity is also an issue regarding better understanding of this complex ecosystem. While important efforts to assess reef health status such as the Atlantic and Gulf Rapid Reef Assessment (AGRRA) protocols are tools used worldwide by the coral reef scientific community, they do not include the survey of geomorphological parameters such as rugosity, roughness and detailed dimensions of the reef studied. If global protocols included this type of information, reef hydrodynamic modelling would be able to advance greatly.

As previously stated, most coral reefs are located in developing nations, which poses logistic and financial difficulties for field surveys. Nevertheless, local information is necessary and “one-size-fits-all” approaches should be avoided. For example, Monismith (2007) identified that most scientific efforts towards understanding colony-scale hydrodynamics, which is crucial in the study of reef rugosity, has concentrated on branching corals. However, if we consider the case study presented herein, most of the relevant reef-building coral species in the area are massive in form (e.g. *Mussismilia hispida*, *Siderastrea stellata*, *Mussismilia braziliensis*, Leão et al., 2003). Therefore, there are still many questions about the interaction of Brazilian coral reefs in general with hydrodynamic parameters. Moreover, as discussed by Ruckelshaus et al. (2015), local scientists are in fact the best equipped actors to guarantee the longevity of a study, especially one that requires frequent field visits and eventual adjustments to fit local reality. Thus, international efforts should always include training opportunities that can allow locals to take ownership over the projects developed, ultimately honing a sense of belonging and will to carry on the work that has begun.

Still regarding the dangers of generalizing information, while the fringing coral reefs of the present case study were shown to efficiently decrease wave height and wave energy, the Archipelago of Tinharé-Boipeba presents important areas under coastal erosion (Silva et al., 2009; Dominguez & Corrêa-Gomes, 2011). Although it may seem contradictory that a coastline bordered by coral reefs with the capacity to offer shoreline protection is under erosion, this is not an isolated finding (Fernandino et al., 2018b). As discussed by Costa et al. (2016), the combination of widespread coral reef degradation and sea-level rise can increase wave transmission over a reef system, leading to coastal erosion. Reguero et al. (2018) also observed that shoreline erosion increased in Grenada possibly due to coral reef degradation. The results of the present study indicated that most of the areas under erosional processes were associated with rip currents, which could be an indication that the presence of reef structures can cause an intensification of wave-induced coastal currents, increasing sediment transport. Moreover, the archipelago presents several areas of inadequate human occupation, as reported by Silva et al. (2009), which has led to sedimentary imbalance.

There is a clear demand for more detailed studies regarding shoreline protection delivered by coral reefs, particularly considering the relevance of this service in face of climate change scenarios (Spalding et al., 2014; Reguero et al., 2018). However, studies should also investigate the interaction among reef attributes, hydrodynamic aspects of the adjacent marine environment and the relevant benefits delivered to society. Although SMC-Brasil is not currently able to simulate all hydrodynamic processes involving reef systems, the framework allows a rapid and relatively simple qualitative evaluation of wave and current patterns in a given area, which improves access to information and can help researchers and decision-makers develop better evidence-based strategies for coastal management.

5 Conclusions

This was the first application of SMC-Brasil to assess the capacity of wave attenuation by coral reefs. Moreover, coastal modelling systems had not been used in the study site at this level of detail so far, and fringing reefs have so far been less studied regarding coastal dynamics. Generalizations and lack of interdisciplinarity were found to be limiting factors for this type of study. This issue should be addressed in other sites worldwide to improve the application of coastal modelling tools, particularly for management purposes. Identifying the potential benefits provided by natural systems has numerous advantages and can serve as a stepping stone to reach adequate ecosystem-based management strategies to deal with issues such as the coastal erosion observed in the Archipelago of Tinharé-Boipeba.

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CAPÍTULO 4

ARTIGO 3 – ASSESSING SEA-LEVEL RISE IMPACTS ON CORAL REEF SHORELINE PROTECTION IN A DATA-DEFICIENT SITE

Highlights

- Coral reefs protect the shoreline against sea-level rise.
- Densely populated areas would become highly vulnerable without coral reefs.
- Open source data is essential for better management strategies.
- The methodological framework used was flexible and adequate for data-deficient sites.

Abstract

Coral reefs have been shown to decrease coastal vulnerability by providing shoreline protection. However, in face of expected sea-level rise, the capacity of providing this ecosystem service can be compromised. With most coral reefs located in areas that lack baseline information, valuable coastal vulnerability assessments become limited. Thus, the objective of the present study was to assess the effects of sea-level rise scenarios on the capacity of providing shoreline protection by a coral reef system located in Brazil, proposing a flexible methodological framework that is appropriate for management at data-deficient sites. The framework begins with considerations on literature review and how this type of information (which may consist also of reputable gray literature) can be used as proxies for biotic and abiotic factors. After this initial step, options are given regarding how sea-level variation scenarios can be developed for a given study area. Finally, the framework suggests the use of the InVEST coastal vulnerability model to analyze changes in shoreline protection. In the study case presented, sea-level rise was calculated as 6 to 8 mm/year, considering the horizon years of 2070 and 2100, using SMC-Brasil. Modelling showed that the archipelago studied presented intermediate vulnerability to erosion and flooding, but with several important areas for human occupation and tourism activities expected to become highly vulnerable if coral reefs cannot provide shoreline protection. Despite limitations of the use of combined models, results show a general trend of increasing vulnerability, particularly with the loss of natural habitats. Climate change mitigation strategies should prioritize increasing resilience by decreasing local impacts. Moreover, despite the susceptibility of coral reefs to climate change, these ecosystems can be key partners in coastal management strategies to adapt to future climatic conditions.

Keywords: climate change; ecosystem services; open data; InVEST; SMC-Brasil.

1. Introduction

Climate change effects are already perceived in ocean and coastal ecosystems and are expected to become more intense over coming years (Ruckelshaus et al., 2013). Sea-level rise is one of the main issues associated with global climate change, presenting a myriad of implications to coastal environments. Fernandino et al. (2018) lists increased flooding and erosion, groundwater salinization, coastal squeeze, and loss of intertidal habitats as some of the most concerning impacts of this climate change effect alone.

The 5th assessment report of the Intergovernmental Panel on Climate Change (IPCC) states that mean sea-level rise rates recorded since the mid-19th century have been higher than the mean rate of the last two millennia (IPCC, 2014). The report associates this information with a potential increase in the degree of exposure and vulnerability of human populations and ecosystems. Therefore, essential ecosystem services, which are the benefits obtained from ecosystems that contribute to human well-being, are expected to be affected in the scenarios predicted by the IPCC. These benefits include provision of food, habitat support, tourism and recreation opportunities, erosion regulation, among many others. However, there are still important gaps in the understanding of climate change effects on the supply of coastal and marine ecosystem services, which have been so far less studied than their terrestrial counterparts (Runting et al., 2017).

Although there are uncertainties regarding the magnitude of sea-level rise, Nicholls and Cazenave (2010) state that sea-level rise rates in general are expected to increase throughout the 21st century. However, projections are sensitive to time and spatial scales, with regional estimates varying significantly from global ones in terms of magnitude (Rhein et al., 2013; Carson et al., 2016). Thus, regional and local scale investigations are paramount to allow effective mitigation and adaptation strategies within coastal management. Yet most decision-makers in coastal zones are ill-prepared for the task of assessing climate change impacts and appropriate management strategies (Fernandino et al., 2018). This is in part due to lack of information regarding coastal environments and an unintegrated approach towards ecosystems.

Coastal habitats have been shown to play an important role in naturally mitigating climate change effects such as sea-level rise. As shown by Arkema et al. (2013), 67% of the USA coastline is currently protected from storm surges and rising sea levels due to the presence of coastal forests, coral and oyster reefs, marshes, dunes, seagrass beds, kelp forests and additional intertidal aquatic vegetation. With coral reefs frequently labeled as the most vulnerable ecosystem to climate change, it seems a paradox that this same habitat can be a key player in mitigating the negative impacts of this phenomenon by protecting the shoreline from incoming waves. However, as discussed by Spalding et al. (2014), coral reefs have indeed been shown to be an important element in reducing damages from coastal hazards and in adapting to climate change.

The current literature still lacks reports that compare the capacity of wave energy and wave height attenuation by different reef morphologies (Elliff and Silva, 2017). Nevertheless, hydrodynamic processes can vary greatly between reef systems (e.g. fringing reef vs. barrier/atoll) (Taebi and Pattiaratchi, 2014). As indicated by Quataert et al. (2015), while some correlations can be made between different morphologies (i.e. steep fore reef slope, relatively wide reef flat and hydrodynamically rough bathymetry, which are common features for both atolls and fringing reefs, for example), the biological community, geology and hydrodynamic conditions to which these reefs are subjected to are extremely variable.

Moreover, the impacts of climate change on ecosystem services in general are likely to overly affect developing nations, which are less able to adapt to these impacts (Srinivasan, 2010). As discussed by Mackay et al. (2018), the data needed for planning adaptation and resilience strategies in the context of climate change are often unavailable when needed, despite advances in the digital information age. Marine data in particular tend to be scarcer, hard to obtain, and are frequently limited in spatial and temporal scales (Gandra et al., 2018).

Thus, the objective of the present study was to assess the effects of sea-level rise scenarios on the capacity of providing shoreline protection by a coral reef system located in Brazil, proposing a flexible methodological framework that is appropriate for coastal management at data-deficient sites.

2. Study area

The coastal archipelago of Tinharé-Boipeba (Fig. 1) is located in the state of Bahia, eastern coast of Brazil, within the Camamu Bay. The region has been established as a type of environmental protection area that in Brazil is considered as a sustainable use conservation unit. This means that the islands can include private and public areas with human occupation, limiting some forms of exploitation but allowing activities such as tourism and small-scale fisheries. However, despite this protection status, the archipelago suffers from chronic human impacts due to poor coastal management strategies (Elliff and Kikuchi, 2017). As shown in Fig. 2, the archipelago experiences various forms of environmental conflict in a highly geodiverse setting.

This situation has consequently affected the fringing coral reef system that borders most of the two major islands, Tinharé and Boipeba. Brazilian coral fauna presents low diversity and high endemism, which adds to the uniqueness of these habitats. The main coral species found in the archipelago are *Siderastrea* spp., *Mussismilia hispida*, *Montastraea cavernosa*, *Mussismilia harttii*, *Mussismilia braziliensis*, *Agaricia agaricites*, *Porites astreoides* and *Millepora alcicornis* (Elliff and Kikuchi, 2017). However, data on the coral reefs of the archipelago of Tinharé-Boipeba are still scarce. As reported by Leão et al. (2003), the first Brazilian coral reefs reported in the literature were these of the Camamu Bay, but the region has so far received less attention than other important reef areas in the country (e.g. the Abrolhos Bank or the Todos os Santos Bay). More recently, Leão et al. (2010) observed low coral reef vitality indices in the area, which poses a concerning condition particularly regarding the delivery of ecosystem services.

The coastline of the region where the archipelago is located, which is known as Costa do Dendê, is highly indented. Marine transgression and regression events during the Quaternary have molded the coastline to how it is currently found (Silva et al., 2009). The archipelago is situated on the narrowest stretch of the continental shelf in the state and presents a semidiurnal meso-tidal regime.

Regarding sea-level rise projections, Nicholls and Cazenave (2010) determined that the Brazilian coast has experienced increases of 2-5 mm/year based on satellite altimetry data from October 1992 to July 2009. Though these values were defined based on a global scale, there is a clear trend towards an increase in mean sea level for coastlines in the Southwestern Atlantic. Thus, the study site is expected to become increasingly more vulnerable to coastal flooding and erosion and should be prepared to apply adaptation and mitigation management strategies in the near future.

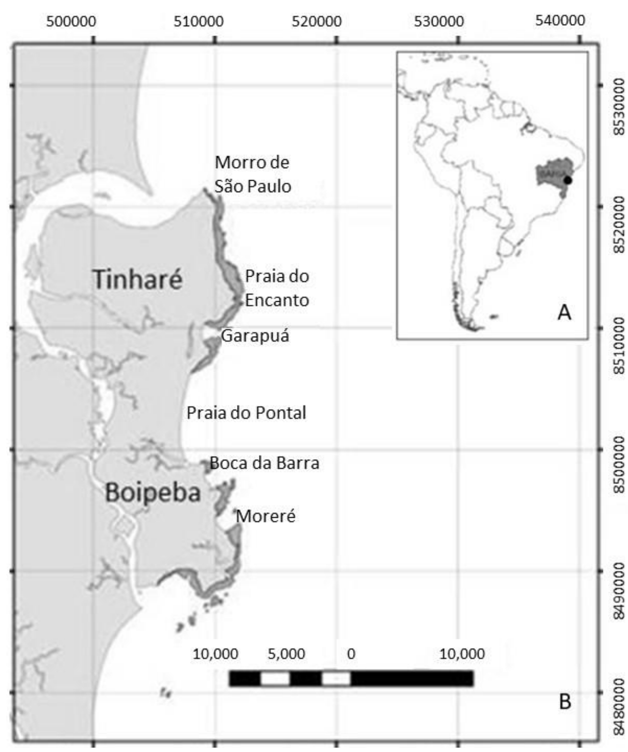


Figure 1. The coastal archipelago of Tinharé-Boipeba, located on the eastern coast of Brazil within the state of Bahia (A). Fringing coral reefs (darker shade of gray) border most of the shoreline of the two main islands (B).

Figure 2. Situations of inadequate human occupation near the shore (A) and lack of sand strip during high tide (B) are signs of potential land use conflicts in the region, while the presence of cliffs (C) and emerged coral reefs during a low tide (D) are examples of the geodiverse setting of the Archipelago of Tinharé-Boipeba, Brazil.

3. Methods

As previously mentioned, developing countries such as Brazil present important data limitations regarding coastal environments (Almeida et al., 2015; Gandra et al., 2018). The methodological framework used in the present study was carefully planned to accommodate these common limitations in coastal management. Fig. 3 illustrates the general steps taken to address the three main stages of the present study: literature review, development of sea-level change scenarios, and assessment of coastal vulnerability under each scenario.

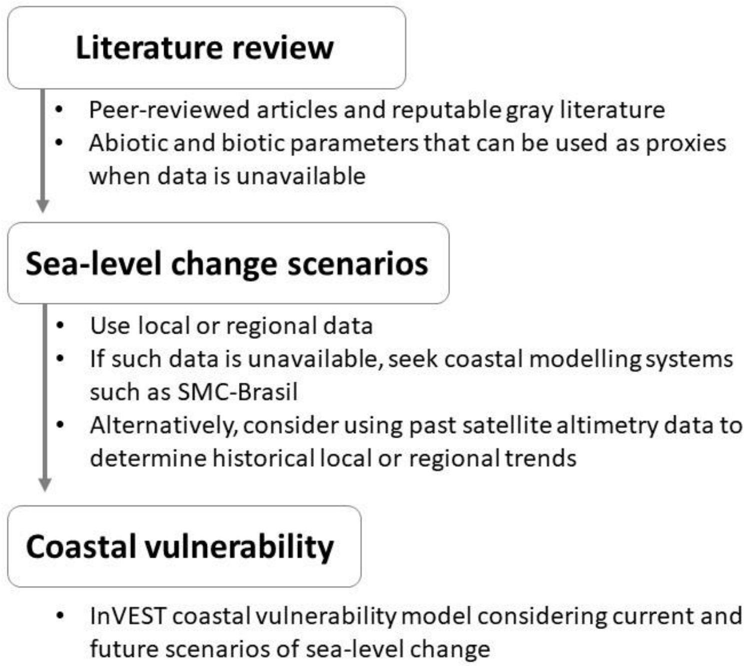


Figure 3. Methodological framework used to assess potential of shoreline protection provided by coral reefs under sea-level change scenarios in a data-deficient site.

3.1. Literature review

Though literature reviews are an essential part of any scientific project, this step may be overlooked at times, which can lead to biased outcomes. While the objective of the present study was not to conduct an exhaustive literature review regarding the study site, several parameters of the coastal environment studied were necessary to carry out the following stages of this investigation. Abiotic and biotic parameters of marine and coastal ecosystems can be used as proxies to define several aspects associated with human and natural uses (Gandra et al., 2018). Thus, given the data deficiency of the study area, the literature review to establish baseline information encompassed not only peer-reviewed articles but also reputable gray literature (e.g. theses, dissertations, government reports), to guarantee better representation of information that may not have been published in scientific journals or that may be of a more technical nature.

Searches were conducted in online databases, such as Web of Science, Science Direct, Google Scholar, Scopus, and Portal de Periódicos CAPES, the latter of which is a scientific repository maintained by the Brazilian government. All publications concerning the archipelago were sorted according to information provided and the references cited in each were assessed for relevance to the present study. Data gathered regarding the coral reefs of the archipelago, geological and oceanographic information, and land use patterns were organized and later applied in the models detailed in sections 3.2 and 3.3.

3.2. Sea-level change scenarios

The Brazilian coastal modelling system SMC-Brasil was used to establish sea-level rise projections at a regional scale. SMC-Brasil was developed in a partnership between the Environmental Hydraulics Institute of the Universidad de Cantabria (IHCantabria), Spain, and the Brazilian Ministry for the Environment (González et al., 2016). The system encompasses a framework of documents and coastal dynamics models intended to assist coastal managers and researchers to better understand coastal processes and improve management actions in Brazil. SMC-Brasil was designed based on the need to characterize coastal dynamics under current and future scenarios despite the scarcity of local data (Almeida et al., 2015). To do so, SMC-Brasil is composed of a database with marine hydrodynamic parameters (waves, sea level, bathymetry, and coastline) that are used for the reanalysis of 60 years of wave and tide data, with temporal resolution of one hour and grid of 1 km^2 (González et al., 2016). By already including these data within the system’s framework, SMC-Brasil overcomes some of the most important challenges regarding data acquisition in coastal modelling.

Regarding bathymetry, the default dataset of the system is composed of the nautical charts made available by the Directorate of Hydrography and Navigation of the Brazilian Navy, though users are able to input additional information. As stated by Gandra et al. (2018), while the best public dataset for bathymetric data in Brazil are these nautical charts, their main purpose is to assist navigation. Thus, an area where this activity is not of prime importance, such as the study site of the present investigation, has less detailed nautical charts.

To surpass this deficiency, aerial images obtained at no cost from Google Earth Pro and a coral reef shapefile available from Dominguez and Corrêa-Gomes (2011) were used to manually correct bathymetry in the archipelago of Tinharé-Boipeba.

To produce the sea-level rise projections report in SMC-Brasil, representative cases were selected from the wave climate data, which are propagated to the coastline of interest through the maximum dissimilarity method (Camus et al., 2011). The user's manual is available at <http://smcbrasil.ihcantabria.com/descargas/> and provides a detailed account of the methodologies used within the system (SMC-Brasil, 2017).

The report brings information on global and regional median sea-level rise (m) for the horizon years of 2070 and 2100 considering Representative Concentration Pathways (RCP) scenarios 4.5 and 8.5, following the formulations proposed by IPCC (2013) and Slangen et al. (2014). The first scenario, RCP 4.5, regards a future situation of stabilization in carbon emissions, not surpassing 4.5 W/m^2 by 2100. In turn, the second, RCP 8.5, is a more pessimistic scenario, which reflects an increase in carbon emissions leading to 8.5 W/m^2 by 2100.

3.3. Coastal vulnerability model

The potential for shoreline protection provided by the coral reefs in the archipelago of Tinharé-Boipeba was estimated using the coastal vulnerability model of the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) software, version 3.4.4. InVEST is a free, open-source tool developed by the Natural Capital Project and can be used for mapping and valuing ecosystem services and goods for an ecosystem-based approach towards environmental management. The software is available at <www.naturalcapitalproject.org>, with detailed descriptions of each model in the user guide (Sharp et al., 2015).

The coastal vulnerability model provides a ranking of areas according to their vulnerability towards coastal flooding and erosion. This is calculated from an exposure index, which compiles information on seven bio-geophysical variables: geomorphology, relief, natural habitats, net sea-level change, wind exposure, wave exposure, and surge potential depth contour (Sharp et al., 2015). Default data are provided within the InVEST package to overcome data-deficiency regarding several of these parameters, which proved to be very useful in the present context.

Similar to the data used in SMC-Brasil, coral reef shapefiles available from Dominguez and Corrêa-Gomes (2011) were used as habitat input, while the geomorphology shapefile was designed based on previous data published by Elliff and Kikuchi (2017). Moreover, the scenarios obtained from SMC-Brasil modelling were used to define net sea-level change in mm/year. The exposure index ranked coastline segments measuring 250x250 m on a scale of 1 (low) to 5 (high).

Thus, to assess the potential of shoreline protection, two scenarios of coastal vulnerability were modelled: with coral reefs and without coral reefs. Each scenario comprised three cases of sea level rise: current sea level, conservative sea-level rise rate, and pessimistic sea-level rise rate. Following the methodology of Arkema et al. (2013), all variables were weighted equally, and the level of vulnerability was mapped using quartiles to define the areas of highest (upper 25%), intermediate (central 50%) and lowest (lower 25%) vulnerability.

4. Results

4.1. Mean sea-level projections

The projections of mean sea level variations for the archipelago, considering RCP scenarios 4.5 and 8.5 and the horizon years of 2070 and 2100, are presented in Table 1. Global and regional projections presented similar magnitudes for each of these years.

For the year of 2070, the conservative scenario (RCP 4.5) showed an increase of 0.33 m in sea level, while the more pessimistic scenario (RCP 8.5) presented a median rise value of 0.39 m, for the regional projections. This variation represents an approximate sea-level rise rate of 6-7.5 mm/year.

By the year of 2100, the expected regional sea-level increase for the RCP 4.5 scenario was observed as 0.51 m, while for the RCP 8.5 scenario this regional variation reached a median value of 0.69 m. For this horizon year, the approximate sea-level rise rate reached 6-8 mm/year, only slightly higher than the projections for 2070.

Thus, conservative and pessimistic sea-level rise rates considered for the InVEST coastal vulnerability model were 6 and 8 mm/year, respectively.

Table 1: Variation of mean sea level (in meters) in the archipelago of Tinharé-Boipeba, Brazil, for the horizon years of 2070 and 2100 according to RCP 4.5 and RCP 8.5 scenarios of the IPCC.

	Global RCP 4.5[1]		Global RCP 8.5[1]		Regional RCP 4.5[2]		Regional RCP 8.5[2]	
Year	**Median**	**CI90%**	**Median**	**CI90%**	**Median**	**CI90%**	**Median**	**CI90%**
2070	0.32	0.20	0.39	0.23	0.33*	0.10*	0.39*	0.14*
2100	0.49	0.35	0.70	0.45	0.51	0.17	0.69	0.27

*The regional projection for the year of 2070 was obtained from the estimate for the year 2100, considering the percentage of change in the global level between these two horizon years.

[1]Projection according to the formulations proposed in IPCC AR5 (IPCC, 2013).

[2] Projection according to the formulations proposed by Slangen et al. (2014).

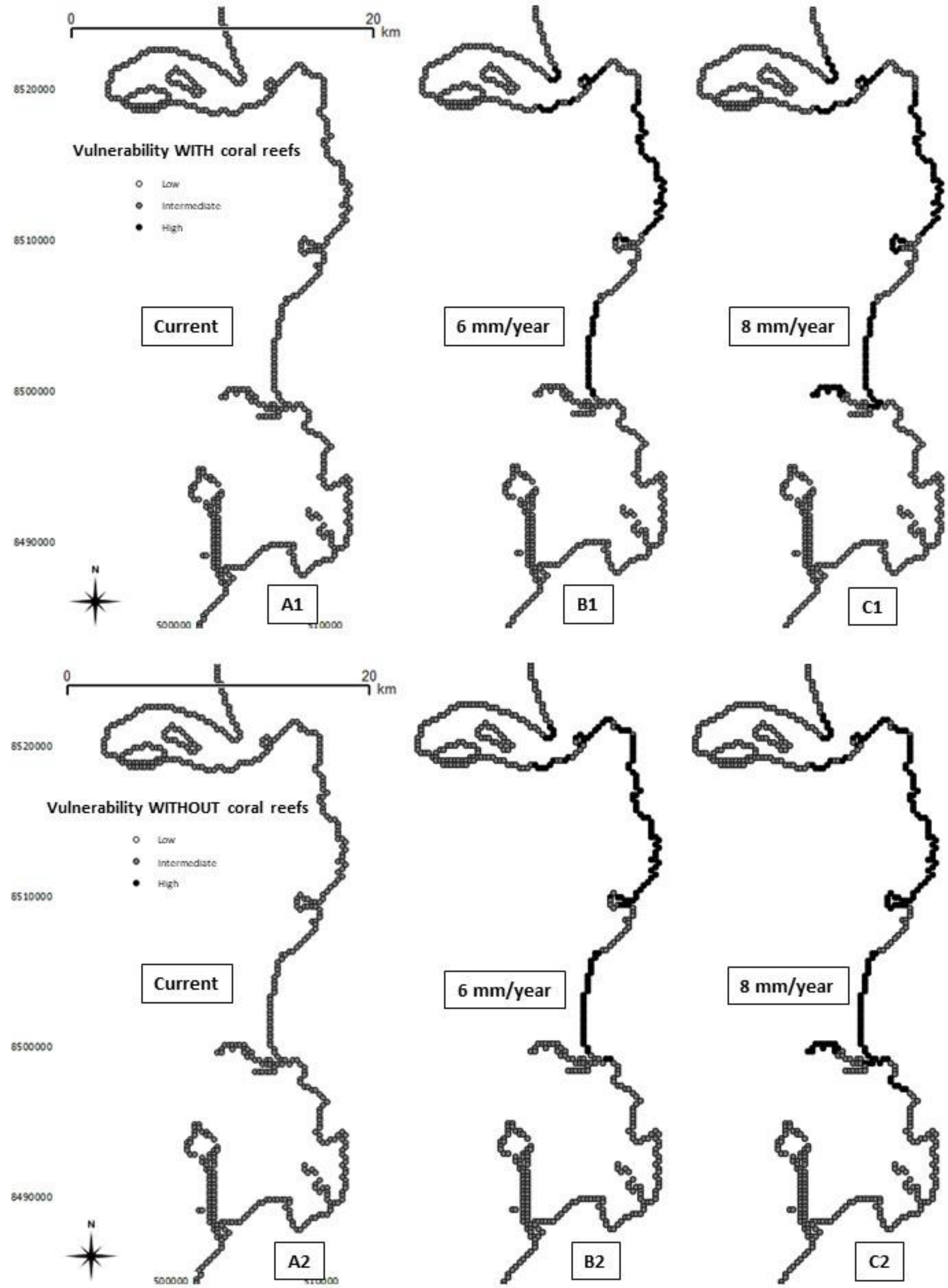
4.2. Coastal vulnerability in future sea-level rise scenarios

The categories of coastal vulnerability (low, intermediate and high) found for each scenario modelled along the islands are shown in Figs. 4 and 5. The current scenario showed intermediate coastal vulnerability (central 50% of the rank attributed) with and without coral reefs. As expected, even the lowest increment in sea level caused a general increase in vulnerability towards flooding and erosion along the islands, with several areas reaching high vulnerability due to loss in shoreline protection by coral reefs. Moreover, while the pessimistic scenario of sea-level rise without coral reefs presented mostly high vulnerability areas, the conservative scenario without coral reefs was not so different. In fact, this conservative scenario without coral reefs presented more highly vulnerable areas than the pessimistic scenario with coral reefs, indicating the importance of this ecosystem for local shoreline protection in face of climate change.

One of the longest stretches of shoreline affected by higher vulnerability was the beach of Praia do Pontal, southern portion of the island of Tinharé (see Fig. 1 for names of beaches). This sandy beach is the only one that is not bordered by reefs, which increases its exposure to incoming waves. Beaches from the northeastern portion of the same island were also classified as highly vulnerable even with the lowest increase of sea-level rise and presence of coral reefs. This area presents intense human occupation near the shoreline, with a narrow sand strip (see Fig. 2b).

The small pocket beach of Garapuá presented mostly intermediate vulnerability under the conservative sea-level rise scenario with coral reefs and was only slightly more affected under the pessimistic scenario. However, once coral reefs were removed from the coastal vulnerability model, high vulnerability predominated in Garapuá under both sea-level rise situations.

Morro de São Paulo (northern tip of the island of Tinharé) and the northern portion of the island of Boipeba also showed important variations in coastal vulnerability under each scenario. These are two of the most densely occupied areas of the archipelago and both presented intermediate vulnerability with the presence of coral reefs but became predominantly highly vulnerable in the scenario without this ecosystem.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Vulnerability WITH coral reefs
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Vulnerability WITHOUT coral reefs
Low
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Figure 4. Coastal vulnerability in the archipelago of Tinharé-Boipeba considering the two scenarios modelled: with coral reefs present (top three figures, A1, B1 and C1) and without coral reefs present (bottom three figures, A2, B2 and C2). Each scenario consisted of three cases: A) Current, B) Conservative sea-level rise (6 mm/year), and C) Pessimistic sea-level rise (8 mm/year).

5. Discussion

To take advantage of the ecosystem service of shoreline protection provided by coral reefs, scientific efforts should be focused on understanding how this service is currently delivered and what can be expected under future scenarios considering each case. As discussed by Principe et al. (2012), while investigations on wave energy attenuation processes have advanced, there is still a gap in knowledge regarding shoreline protection as an ecosystem service per se. This means to connect the physical phenomenon of attenuating wave height and wave energy with delivering benefits of decreased vulnerability to human communities. The results of the present study case demonstrate that the coral reefs of the archipelago of Tinharé and Boipeba have an important role in shoreline protection and should be valued for this. The most densely populated areas of the islands would become highly vulnerable to erosion and flooding if the coral reefs were no longer able to provide this ecosystem service, which currently limits vulnerability to an intermediate classification.

Vulnerability can be understood as the combination of characteristics and circumstances that make a community, system or asset susceptible to damages caused by a hazard (UNISDR, 2009). Thus, the methodological framework presented allowed an assessment of climate-change driven coastal vulnerability, focusing on the loss of shoreline protection by a natural habitat.

The present study showed that the archipelago is currently under intermediate coastal vulnerability to erosion and flooding and would remain within the broad intermediate category even without coral reefs. As described by Arkema et al. (2013), the intermediate category encompasses the central 50% of the coastal vulnerability rank calculated by the model. Thus, it is possible that local changes occurred between these two scenarios, but these were not enough to elevate or decrease the classification of vulnerability. Elliff and Kikuchi (2017) found that the fringing reefs in this archipelago currently protect most of the shoreline against coastal erosion and flooding. However, the same authors showed concern regarding the coincidence between areas that rely on shoreline protection from these coral reefs and areas that are under high habitat risk of losing their capacity to provide services due to environmental degradation. This would be the case of densely populated areas such as Morro de São Paulo, which is also where most tourism infrastructure is located.

The coral reefs of the archipelago of Tinharé-Boipeba are under similar impacts of other coastal reefs around the world. Leão et al. (2010) reported that Brazilian reefs located less than 5 km from the coastline are the most impacted by sewage pollution, diseases, high sedimentation rates, water turbidity, and bleaching events. These chronic human pressures decrease coral reef resilience and, thus, threaten the efficient delivery of ecosystem services (Elliff and Kikuchi, 2015). In addition, Hernández-Delgado (2015) alerted to the threat of synergetic and cumulative impacts in the face of climate change. Thus, decreasing local impacts should be a priority within climate change mitigation strategies in coastal management.

Access to open data and public datasets was another crucial aspect of the present study. The thorough literature review helped compile information already known for the area. However, important information was sometimes unavailable not because it had not been surveyed, but because it was protected by contracts of intellectual property. This was the case of some bathymetry surveys conducted in the area in the context of oil and gas exploration in the Camamu Bay. The authors sought to access the data, but these requests were either denied (despite the academic nature of the request) or the data was too costly. Similar situations were observed by Mackay et al. (2018) for Pacific small island developing states, who identified several barriers and possible underlying causes to good climate change information and knowledge management.

Assessing the potential for shoreline protection and other ecosystem services by coral reefs can seem a dauting task given the complexity of this ecosystem and considering that most coral reefs are located in developing countries, which frequently lack baseline and long-term environmental monitoring data. Moreover, relatively few studies regarding climate change impacts to ecosystem services integrate decision making, with only a small portion of these encompassing coastal environments (Runting et al., 2017). However, as discussed by Rumson and Hallett (2018), the current movement observed towards open source data across the globe is promoting a valuable opportunity for evidence-based decision making. Moreover, Rudd (2017) identified environmental conservation, social impacts, co-management strategies and economic impacts as some of the most relevant current issues in ocean and coastal sustainability challenges and solutions. All these aspects are directly relevant to coastal and marine ecosystem services. With increasing information and attention towards these issues, resources can be adequately directed, and important gaps can be filled, promoting better management actions and blue growth.

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CAPÍTULO 5
CONCLUSÕES

Mudanças climáticas não são algo inédito na história do nosso planeta, porém a velocidade observada nas alterações deste fenômeno é. A subida do nível do mar é um dos impactos das mudanças climáticas de maior visibilidade, sendo associada a cenários de catástrofes na zona costeira. No presente trabalho foi demonstrado o quão importante é o serviço de proteção à linha de costa fornecido por recifes de coral atualmente e no futuro para a área de estudo; como este benefício ainda não é completamente compreendido na literatura; e o quanto os recifes de coral são tão vulneráveis às mudanças climáticas quanto potenciais ecossistemas estratégicos para adaptação às novas condições do clima.

Observou-se que ainda há lacunas na literatura quanto à forma de fornecimento de proteção à linha de costa por tipos morfológicos distintos de recifes de coral. Além disso, estudos na área de atenuação de energia e altura de ondas nem sempre correlacionam esse fenômeno físico aos benefícios socioeconômicos sentidos por populações humanas costeiras.

Alguns dos atributos recifais mais relevantes para avaliação desse serviço ecossistêmico são a declividade da frente recifal, a rugosidade, as dimensões e o tipo morfológico do recife, e a extensão do topo recifal. No entanto, protocolos internacionais de avaliação de recifes de coral frequentemente não incluem o levantamento de dados geomorfológicos. Isso dificulta análises mais robustas sobre proteção à linha de costa e outros serviços ligados à geologia do recife de coral, principalmente em cenários de mudanças ambientais.

Apesar do sistema de modelagem costeira SMC-Brasil não ter sido desenvolvido para simular todos os processos hidrodinâmicos envolvendo sistemas recifais, o pacote de modelos e metodologias desse sistema permite uma avaliação qualitativa relativamente rápida e de simples aplicação para entender os padrões de ondas e correntes costeiras de uma dada área, além de calcular projeções de subida do nível do mar em nível regional. Essa informação inédita aumenta o acesso de pesquisadores a informações relevantes para desenvolver estratégias baseadas em evidências dentro de um contexto de gerenciamento costeiro integrado.

Os recifes de coral em franja do arquipélago de Tinharé e Boipeba de fato fornecem o serviço ecossistêmico de proteção à linha costa à população local. No entanto, mesmo se esses recifes se mantiverem sem perdas de cobertura viva significativas, estima-se um aumento generalizado do nível de vulnerabilidade costeira à erosão e inundação. Dessa forma, caso os recifes de coral do arquipélago não sejam mais capazes de fornecer esse serviço, áreas de grande importância econômica e social se tornarão altamente vulneráveis com as projeções de subida do nível médio do mar até o final do século.

Ao passo que um cenário de total ausência de recifes de coral seja improvável, também não é esperado que os recifes continuem imutáveis ao longo dos próximos anos. Os efeitos sinergéticos entre impactos locais e efeitos das mudanças climáticas ainda são pouco compreendidas na prática. Sabe-se que os corais são particularmente suscetíveis a aumentos da temperatura média do mar e à acidificação dos oceanos, por exemplo, levando-os a estados de branqueamento e enfraquecimento da estrutura carbonática que compõem o recife. No entanto, a resposta específica a cada um desses impactos é variável, portanto é cedo demais para considerar o ecossistema recifal como extinto dentro dos cenários futuros esperados.

A sobrevivência do recife de coral e, consequentemente, o fornecimento eficaz dos serviços ecossistêmicos que beneficiam numerosas populações humanas, depende de um balanço em sua resiliência. Esta característica de recuperação frente a perturbações é essencial para a manutenção de qualquer ecossistema. Sugere-se que atuar sobre os impactos crônicos antrópicos já conhecidos na área, como a sobrepesca, ocupação irregular na costa, poluição e turismo desenfreado, deve ser o primeiro passo para garantir a resiliência dos recifes de coral, permitindo que estes estejam aptos a se adaptarem às novas condições climáticas projetadas.

Um empecilho importante observado no presente trabalho foi o acesso a dados e informações técnico-científicas não só da costa do arquipélago de Tinharé e Boipeba, mas do Brasil. Em uma era digital, espera-se rapidez e robustez de avaliações. No entanto, a velocidade dessa demanda é maior do que a velocidade observada para a disponibilização de dados essenciais para avançar cientificamente. Tanto o SMC-Brasil quanto o *software* InVEST foram desenvolvidos com preocupação nesse sentido, ambos incluindo dados padrão (*default*) para suprir ausências de informações básicas. Não há dúvidas de que o presente trabalho apresentou limitações devido a essa situação. No entanto, espera-se que os resultados inéditos e a proposta metodológica aqui apresentados sirvam de exemplo de resiliência científica.

Dessa forma, sugere-se que os próximos passos nesta linha de pesquisa envolvam o aumento da disponibilização de dados de acesso livre (*open source data*), inclusão de dados geomorfológicos em protocolos internacionais de avaliação de recifes de coral, desenvolvimento de modelos de dinâmica costeira que incluam a rugosidade do recife em seus cálculos, melhorar o entendimento entre as sinergias de impactos locais e efeitos de mudanças climáticas sobre o ecossistema recifal, e propor e testar estratégias de recuperação, mitigação e adaptação que possam ser plenamente implementados e monitorados.

APÊNDICE A – JUSTIFICATIVA DA PARTICIPAÇÃO DOS CO-AUTORES

O artigo 2, apresentado no capítulo 3 (*Wave attenuation and shoreline protection by a fringing reef system*), é de autoria de Carla I. Elliff, Iracema R. Silva, Verónica Cánovas e Mauricio González. As primeiras duas autoras são a presente aluna e orientadora. Os dois seguintes autores são pesquisadores do Instituto de Hidráulica Ambiental da Universidade da Cantábria, Santander, Espanha. Ambos foram essenciais em meu treinamento para a aplicação do sistema de modelagem SMC-Brasil utilizado para as análises do artigo. Ademais, ambos participaram ativamente na escrita e revisão do manuscrito.

Os artigos 1 e 3 apresentados nos capítulos 2 e 4 são de autoria de Carla I. Elliff e Iracema R. Silva, a presente aluna e sua orientadora, respectivamente.

ANEXO A – REGRAS DE FORMATAÇÃO DA REVISTA MARINE ENVIRONMENTAL RESEARCH (ARTIGO 1)

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Define abbreviations that are not standard in this field at their first occurrence in the article: in the abstract but also in the main text after it. Ensure consistency of abbreviations throughout the article.

Acknowledgements

Collate acknowledgements in a separate section at the end of the article before the references and do not, therefore, include them on the title page, as a footnote to the title or otherwise. List here those individuals who provided help during the research (e.g., providing language help, writing assistance or proof reading the article, etc.).

Formatting of funding sources

List funding sources in this standard way to facilitate compliance to funder's requirements:

Funding: This work was supported by the National Institutes of Health [grant numbers xxxx, yyyy]; the Bill & Melinda Gates Foundation, Seattle, WA [grant number zzzz]; and the United States Institutes of Peace [grant number aaaa].

It is not necessary to include detailed descriptions on the program or type of grants and awards. When funding is from a block grant or other resources available to a university, college, or other research institution, submit the name of the institute or organization that provided the funding.

If no funding has been provided for the research, please include the following sentence:

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Nomenclature and units

Follow internationally accepted rules and conventions: use the international system of units (SI). If, in certain instances, it is necessary to quote other units, these should be added in parentheses. Temperatures should be given in degrees Celsius. The unit "billion" (109 in America, 1012 in Europe) is ambiguous and must not be used.

Math formulae

Please submit math equations as editable text and not as images. Present simple formulae in line with normal text where possible and use the solidus (/) instead of a horizontal line for small fractional terms, e.g., X/Y. In principle, variables are to be presented in italics. Powers of e are often more conveniently denoted by exp. Number consecutively any equations that have to be displayed separately from the text (if referred to explicitly in the text).

Footnotes

Footnotes should be used sparingly. Number them consecutively throughout the article. Many word processors build footnotes into the text, and this feature may be used. Should this not be the case, indicate the position of footnotes in the text and present the footnotes themselves separately at the end of the article.

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• Make sure you use uniform lettering and sizing of your original artwork.

• Preferred fonts: Arial (or Helvetica), Times New Roman (or Times), Symbol, Courier.

• Number the illustrations according to their sequence in the text.

• Use a logical naming convention for your artwork files.

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• Please note that individual figure files larger than 10 MB must be provided in separate source files.

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References

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Text: All citations in the text should refer to:

1. *Single author:* the author's name (without initials, unless there is ambiguity) and the year of publication;
2. *Two authors:* both authors' names and the year of publication;
3. *Three or more authors:* first author's name followed by "et al." and the year of publication.

Citations may be made directly (or parenthetically). Groups of references should be listed first alphabetically, then chronologically.

Examples: "as demonstrated (Allan, 1996a, 1996b, 1999; Allan and Jones, 1995). Kramer et al. (2000) have recently shown ...."

List: References should be arranged first alphabetically and then further sorted chronologically if necessary. More than one reference from the same author(s) in the same year must be identified by the letters "a", "b", "c", etc., placed after the year of publication.

Examples:

Reference to a journal publication:

Van der Geer, J., Hanraads, J.A.J., Lupton, R.A., 2000. The art of writing a scientific article. Journal of Scientific Communication 163, 51-59.

Reference to a book:

Strunk Jr., W., White, E.B., 1979. The Elements of Style, third ed. Macmillan, New York.

Reference to a chapter in an edited book:

Mettam, G.R., Adams, L.B., 1999. How to prepare an electronic version of your article, in: Jones, B.S., Smith , R.Z. (Eds.), Introduction to the Electronic Age. E-Publishing Inc., New York, pp. 281-304.

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ANEXO B – REGRAS DE FORMATAÇÃO DO ANUÁRIO DO INSTITUTO DE GEOCIÊNCIAS DA UFRJ (ARTIGO 2)

Normas para Publicação

1. O Anuário do Instituto de Geociências é uma publicação oficial da Universidade Federal do Rio de Janeiro – Centro de Ciências Matemáticas e da Natureza, Instituto de Geociências, destinando- -se à divulgação da produção científica de interesse amplo, caráter original e inedito, relacionada com as Geociências. Ao submeter um artigo, o autor(es) do mesmo está realizando de maneira automática a transferência de direitos autorais ao Anuário do Instituto de Geociências da UFRJ.

Não há o pagamento de taxas para a submissão ou para a publicação de artigos no Anuário do Instituto de Geociências.

2. O Anuário do Instituto de Geociências publica Artigos e Comunicações, no âmbito das Geociências.

3. Os textos podem ser redigidos em português, francês, espanhol ou inglês em papel A4.

4. Artigos - podem conter até 15 páginas digitadas em espaço duplo, incluindo ilustrações e referências bibliográficas. Textos maiores poderão ser publicados mediante pagamento dos custos de produção.

5. Comunicações - podem conter até 5 páginas digitadas em espaço duplo, incluindo ilustrações e referências. Destinam-se a divulgar resumos de importantes descobertas recentes.

Preparação Para Encaminhamento

a) Textos

6. Artigos e Comunicações

Uma primeira folha com o título, número de figuras e o índice. Da segunda folha em diante, em sequência, o título, nome completo do(s) autor (es), endereço (caixa postal, logradouro, e-mail, CEP, cidade e Estado), Resumo, Abstract, texto completo, Inserir textos explicativos das ilustrações no corpo do texto, na posição aproximada onde deverão aparecer.

Hierarquizar os títulos e subtítulos em 1, 1.1, 2, 2.1, 2.2 etc.

O Resumo e Abstract devem ter até 25 linhas em Artigos (para textos redigidos em inglês) e até 10 linhas em Comunicações, e serem seguidos de palavras-chave e Keywords, respectivamente. Artigos em português, espanhol ou francês deverão ter o título vertido para a língua inglesa, colocado após a palavra Abstract. Editar o texto e tabelas em Word for Windows, fonte Times New Roman, tamanho 12. As linhas de texto alinhadas à esquerda e em espaço duplo. Todas as margens devem ter 2,5 cm. Digitar as tabelas no modo TABELA. Não remeter CDs e originais.

Envie arquivo digital ".doc" para o endereço eletrônico: ismar@geologia.ufrj.br

b) Ilustrações

7. As ilustrações gráficas, fotográficas e fotomicrográficas serão numeradas sequencialmente, na ordem de sua citação no texto, e consideradas, mesmo pranchas, indiscriminadamente como Figuras.

Não serão aceitos encartes. Todas as ilustrações deverão ser preparadas de forma digitalizada em formato .jpeg com resolução de 300dpi.

8. Legendas e símbolos das ilustrações devem ter dimensões adequadas para permitir legibilidade em eventuais reduções. Explicar todos os símbolos. Colocar escalas gráficas dentro da área das ilustrações. As figuras devem ser preparadas de modo a otimizar o espaço disponível.

c) Referências

9. Citações no corpo do texto, seguir os formatos do seguinte exemplo: Lima (1999), Lima & Silva (1992 a, b), e para três autores ou mais, Lima et al. (2002).

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Pereira, R.; Guimarães Jr., J.A. & Silva Jr., G.C. 2002. Avaliação do Impacto da Captação de Água na Lagoa do Bomfim, RN - Brasil. Revista Águas Subterrâneas, 16 (1): 61 - 68.

Souza, M.L. 1997. Algumas Notas Sobre a Importância do Espaço para o Desenvolvimento Social. Território, 3: 13-35.

Artigos de Publicações Seriadas:

Vicalvi, M.A.; Kotzian, S.C.B. & Forti-Esteves, I.R. 1977. A Ocorrência de Microfauna Estuarina no Quaternário da Plataforma Continental de São Paulo. In: Evolução Sedimentar Holocênica da Plataforma Continental e do Talude do Sul do Brasil, Rio de Janeiro, CENPES/DINTEP, p. 77 - 97. (Série Projeto REMAC 2).

Dissertações e Teses:

Caita, M.B.F. 2000. Angola: Estado-Nação, Movimentos Sociais e Disputas Territoriais. O Caso da Província de Ngagela. Programa de Pós-graduação em Geografia, Universidade Federal do Rio de Janeiro, Dissertação de Mestrado, 67p.

Artigos Publicados em Eventos:

Dias-Brito, D. 1992. Ocorrências de Calcisferas em Depósitos carbonáticos do Atlântico Sul: Impacto na Configuração Paleoceanográfica do Tétis Cretácico. In: SIMPÓSIO SOBRE AS BACIAS CRETÁCICAS BRASILEIRAS, 2, Rio Claro, 1992. Resumos expandidos, Rio Claro, UNESP, p. 30-34.

Livros:

Becker, B. & Egler, C. 1993. Brasil: Uma Nova Potência Regional na Economia-Mundo. Rio de Janeiro, Bertrand Brasil. 267 p.

Capítulos de Livros:

Wanderley, M. D. 2004. Nanofósseis Calcários. In: CARVALHO, I. S. (ed.). Paleontologia. Editora Interciência, p. 285-296.

Análise Pelo Corpo Consultivo

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13. Provas dos Artigos e Comunicações, serão remetidas aos autores (arquivo no formato PDF) para correção antes da impressão. Alterações necessárias deverão ser encaminhadas manuscritas na prova do arquivo PDF.

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ANEXO C – COMPROVANTE DE SUBMISSÃO E ACEITE DO ARTIGO 1

Carla Isobel Elliff <carlaelliff@gmail.com>

Submission MERE_2016_6 received by Marine Environmental Research

1 mensagem

Marine Environmental Research <EviseSupport@elsevier.com> 3 de outubro de 2016 09:33

Responder a: mere@elsevier.com
Para: carlaelliff@gmail.com

This message was sent automatically. Please do not reply.

Ref: MERE_2016_6
Title: Coral reefs as the first line of defense: shoreline protection in face of climate change
Journal: Marine Environmental Research

Dear Ms. Elliff,

Thank you for submitting your manuscript for consideration for publication in Marine Environmental Research. Your submission was received in good order.

To track the status of your manuscript, please log into EVISE® at: http://www.evise.com/evise/faces/pages/navigation/NavController.jspx?JRNL_ACR=MERE and locate your submission under the header 'My Submissions with Journal' on your 'My Author Tasks' view.

Thank you for submitting your work to this journal.

Kind regards,

Marine Environmental Research

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Carla Isobel Elliff <carlaelliff@gmail.com>

Your manuscript MERE_2016_6_R1 has been accepted

1 mensagem

Inna Sokolova (Marine Environmental Research) <EviseSupport@elsevier.com> 23 de março de 2017 07:25

Responder a: inna.sokolova@uni-rostock.de
Para: carlaelliff@gmail.com

Ref: MERE_2016_6_R1
Title: Coral reefs as the first line of defense: shoreline protection in face of climate change
Journal: Marine Environmental Research

Dear Ms. Elliff,

I am pleased to inform you that your paper has been accepted for publication. My own comments as well as any reviewer comments are appended to the end of this letter. Now that your manuscript has been accepted for publication it will proceed to copy-editing and production.

Thank you for submitting your work to Marine Environmental Research. We hope you consider us again for future submissions.

Kind regards,

Inna Sokolova
Editor
Marine Environmental Research

Comments from the editors and reviewers:

ANEXO D – COMPROVANTE DE SUBMISSÃO DO ARTIGO 2

ANUÁRIO IGEO
ISSN 0101-9759
UFRJ IGEO

Rio de Janeiro, 21 de novembro de 2018

De: Anuário do Instituto de Geociências
Para: Carla Isobel Elliff

Manuscrito: **Wave attenuation and shoreline protection by a fringing reef system**
Autor(es): Ellif *et al.*

Declaro, para os devidos fins, que o manuscrito acima mencionado foi submetido para publicação no periódico Anuário do Instituto de Geociências (ISSN 0101-9759) e atualmente encontra-se sob avaliação por revisores *ad hoc*.

Atenciosamente,

Hermínio Ismael de Araújo Júnior
Editor Associado
Anuário do Instituto de Geociências
http://www.anuario.igeo.ufrj.br/

Artigo a ser publicado no Anuário IGEO UFRJ 2019_01

Almir Miranda <almirmir@gmail.com> 12 de fevereiro de 2019 09:23
Para: carlaelliff@gmail.com
Cc: ismar_geologia <ismar@geologia.ufrj.br>, mauricio.gonzalez@unican.es, iracema@pq.cnpq.br, veronica.canovas@unican.es

Bom dia!
Prezados autores.

Em breve estará publicado on-line o Anuário do Instituto de Geociências, Volume 2019-1, no qual seu manuscrito, "**Wave attenuation and shoreline protection by a fringing reef system**" tem previsão de publicação. Atualmente a publicação é conceito B1 na base Qualis para a área de Geociências.

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Obrigado por sua atenção,

Ismar de Souza Carvalho
Editor
Anuário do Instituto de Geociências
http://www.anuario.igeo.ufrj.br/

Almir Miranda da Silva
Produção Editorial
almirmir@gmail.com
21 99933 1311