



UNIVERSIDADE CEUMA
REITORIA
PRO-REITORIA DE PÓS-GRADUAÇÃO, PESQUISA E EXTENSÃO
MESTRADO EM MEIO AMBIENTE

Raoni Blum Tomaz

**SIMULAÇÃO DOS IMPACTOS DA ELEVAÇÃO DO NÍVEL DO MAR NA
COSTA DE MANGUEZAIS DE MACROMARÉS DA AMAZÔNIA
MARANHENSE**

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São Luís
2018

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Dissertação apresentada ao Programa de Pós-Graduação em Meio Ambiente da Universidade CEUMA, como requisito para obtenção do grau de Mestre (a) em Meio Ambiente.

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Resumo

O Brasil possui a maior área contínua de manguezais do mundo, localizado na Amazônia legal. O objetivo do presente estudo é simular a resposta dos manguezais, da parte oriental da Amazônia legal, ao aumento do nível do mar e produzir uma avaliação de vulnerabilidade do manguezal para este trecho da costa brasileira. Foi utilizado um modelo espacialmente explícito, baseado em autômatos celulares e Sistema de Informações Geográficas (SIG) para identificar padrões de resistência, migração e/ou inundação desses manguezais para diferentes eventos de elevação do nível médio do mar (ENMM). A simulação considera 90 eventos de elevação de 0,00318 m a 0,2862 m de acordo com uma progressão aritmética de razão 0,00318 m para o intervalo de tempo do ano de 2010 a 2100. A taxa de ENMM adotada foi de 3,18 mm/ano (0,00318 m/ano). Esta taxa corresponde a uma média dos valores observados para a costa brasileira de meados do século XX até início do século XXI. No final da simulação (ano 2100), a área de mangue original (4.180 km²) foi reduzida para 2.916 km², representando uma perda de 30,24%. A simulação também mostrou significativa migração dos manguezais para o continente, e a perda da área de manguezal original foi compensada por um aumento de 301 km² de novos manguezais para o continente, o que representa um aumento de 7,2% na área total de manguezais (4.481 km² em 2100). Esses resultados sugerem que as florestas de mangues podem apresentar um padrão de aumento de área e migração para o continente a partir da ENMM projetado. Essas descobertas podem ajudar na identificação de corredores de migração para os manguezais da Amazônia e no desenvolvimento de estratégias de adaptação frente à iminente ENMM.

Palavras-chave: Florestas de Mangue, Mudanças climáticas e Elevação do Nível Médio do Mar.

Abstract

Brazil has the largest continuous area of mangrove forests in the world, the Amazon Macrotidal Mangrove Coast (AMMC). The objective of the present study is to simulate the response of eastern Amazonian mangroves to sea-level rise, and to produce a vulnerability assessment for this section of the Brazilian coast. We used a spatially explicit model, based on cellular automata and Geographic Information System (GIS) to identify resistance patterns, migration and/or inundation of these mangroves for different events of sea-level rise (SLR). The simulation considers 90 elevation events from 0.00318 m to 0.2862 m according to an arithmetic progression of reason 0.00318 m for the time interval from 2010 to 2100. The adopted SLR rate was 3.18 mm/year (0.00318 m/year), this rate corresponds to an average of sea elevation values observed for the Brazilian coast during the mid-twentieth century and early twenty-first century. At the end of the simulation (year 2100), the original mangrove area (4,180 km²) was reduced to 2,916 km², representing a loss of 30.24%. Our simulation also showed significant landward migration of the mangroves, and the modeled loss of the original mangrove area was compensated by a net addition of 301 km² of new mangroves inland, a net increase of 7.2% in the total mangrove area (4,481 km² in 2100). These results suggest that mangrove forests in the AMMC can present a pattern of area increase and migration to the continent from the projected SLR. These findings can help the identification of migration corridors for the Amazonian mangroves and the development of adaptation strategies in face of impending SLR.

Keywords: Mangrove Forests, Climate Change and Sea-Level Rise,

Epígrafe

É preciso entender as novas dinâmicas resultantes da ação do Homem no Meio Ambiente. Assim poderemos compreender as consequências dos nossos atos e despertar para ações que minimizem os nossos impactos.

Agradecimentos

A Deus que nos confere a vida e a saúde para termos forças em alcançar algo novo que nos torne pessoas melhores.

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Lista de Abreviaturas

IPCC - Intergovernmental Panel on Climates changes

ENMM - Elevação do Nível Médio do Mar

APA - Área de Proteção Ambiental

PBMC - Painel Brasileiro para Mudanças Climáticas

DAIM - Deslocamento da Área de Influência da Maré

AIM - Área sob Influência da Maré

INPE - Instituto de Pesquisas Espaciais

EMBRAPA - Empresa Brasileira de Pesquisa e Agropecuária

ZEE - Zoneamento Ecológico e Econômico

DHN - Departamento de Hidrografia e Navegação, Marinha do Brazil

AMMC - Amazon Macrotidal Mangrove Coast

GIS - Geographic Information System

SLR - Sea-Leavel Rise

EPA - Environmental Protection Area

ITCZ - Inter-Tropical Convergence Zone

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1 INTRODUÇÃO/REFERENCIAL TEÓRICO

Os manguezais funcionam como um elo entre os ecossistemas marinhos e terrestres, desempenhando um papel vital na conservação da diversidade biológica em regiões tropicais e subtropicais (ROG, CLARKE e COOK, 2017).

Os manguezais possuem adaptações morfológicas e fisiológicas desenvolvidas, que permitem que eles existam em condições de alta salinidade, marés extremas, ventos fortes, altas temperaturas e solos lamacentos e anaeróbios (ALONGI, 2009). Os manguezais também são ecossistemas produtivos, que abrigam uma grande variedade de peixes, caranguejos, camarões e espécies de moluscos (MANSON et al., 2005).

Os manguezais também contribuem com quantidades significativas de matéria orgânica para os ecossistemas costeiros e são considerados locais de intenso processamento biogeoquímico e podem impactar os ciclos globais de carbono e nitrogênio (BUILLON et al., 2008; COHEN e LARA, 2003). Além disso, os densos sistemas radiculares das florestas de manguezais absorvem quantidades significativas de sedimentos, estabilizando os litorais e prevenindo a erosão causada por ondas e tempestades (MAZDA, VOLANSKI e RIDD, 2007).

Ao filtrar os sedimentos, os manguezais também permitem que os recifes de corais e as ervas marinhas realizem suas trocas gasosas com maior facilidade (GILLIS et al., 2014). Juntos, os recifes de corais, as ervas marinhas e as florestas de manguezais fornecem uma série de benefícios ecossistêmicos e estão entre os sistemas naturais mais valiosos do planeta. O valor anual de produtos e serviços fornecidos por florestas de mangue são estimados entre US \$ 200.000 e \$ 900.000 por km² (WELLS et al., 2006).

O aquecimento do sistema climático, decorrente das atividades humanas, é sem precedentes (IPCC, 2013). O aquecimento global está causando mudanças com impactos generalizados em sistemas humanos e naturais, em todos os continentes e em todos os oceanos. Segundo Nicholls (2004), esses impactos nas regiões costeiras incluem inundações e erosão devido à elevação do nível médio do mar (ENMM), a intensificação do ciclo hidrológico (HUNTINGTON, 2006) e mudanças na frequência e intensidade de eventos severos de tempestade (IPCC, 2013).

De todos os efeitos da mudança climática, a ENMM é considerado o principal fator de vulnerabilidade para as florestas de mangue (FIELD, 1995).

Para a presente pesquisa, o conceito de vulnerabilidade adotado é aquele apresentado pelo IPCC (2013), a saber: *vulnerabilidade é o grau pelo qual um sistema é provável ou incapaz de lidar com os efeitos adversos das mudanças climáticas, incluindo a variação climática e seus extremos.*

O Brasil abriga a segunda maior área total e a maior área contínua de florestas de mangue do mundo (SPALDING, KAINUMA e COLLINS, 2010; NASCIMENTO et al., 2013). Portanto, entender a resposta dos manguezais brasileiros aos potenciais impactos decorrentes das mudanças climáticas é um desafio significativo.

É quase impossível reunir essas informações usando métodos tradicionais baseados em campo, já que os manguezais são extremamente difíceis de acessar. Felizmente, a tecnologia de sensoriamento remoto oferece uma alternativa promissora para resolver esse problema de acessibilidade (GREEN et al., 2000; HOWARD et al., 2015).

Nos últimos 20 anos, as técnicas de sensoriamento remoto demonstraram um alto potencial para detectar, identificar, mapear e monitorar as condições e mudanças dos manguezais (GUO et al., 2017; HEUMANN, 2011; KUENZER, 2011; PURNAMASAYANGSUKASIH et al., 2016) . Existem alguns exemplos de estudos de sensoriamento remoto sendo utilizados exclusivamente para mapear a extensão e distribuição dos manguezais brasileiros (LACERDA, MENEZES e MOLISANI, 2007; NASCIMENTO et al., 2013; SOUZA-FILHO, 2005; SOUZA-FILHO, 2009). No entanto, poucos estudos tentaram simular a resposta desses manguezais frente à ENMM.

Em 2009, foi-se proposto um modelo conceitual de resposta das florestas de mangue a um possível aumento na ENMM induzido pelo aquecimento global (SOARES, 2009). De acordo com esse modelo, as respostas dependem das taxas de aumento do nível do mar, taxas de sedimentação, topografia da área e disponibilidade de áreas adequadas para a migração de manguezais em direção ao continente.

Em 2010, foi-se proposta uma metodologia para estimar o grau de vulnerabilidade dos manguezais e populações pesqueiras frente aos impactos

das mudanças climáticas no Complexo Estuarino de Paranaguá, no sul do Brasil.

Em 2011, um estudo brasileiro propôs o uso do reflorestamento de manguezais como uma ferramenta para proteger a Bacia Potiguar (nordeste brasileiro) contra a erosão generalizada e a susceptibilidade da costa resultante das mudanças climáticas e atividades antrópicas (DANTAS, AMARO e COSTA, 2011).

Em 2012, outra pesquisa brasileira analisou o pólen, diatomáceas e isótopos estáveis em uma região de sedimentos dos manguezais da Ilha do Cardoso e determinou que o desenvolvimento de manguezais cessou após um evento erosivo associado à ENMM pós-glacial na região (PESSENDA et al., 2012). As florestas de mangue existentes hoje na região se desenvolveram nos últimos 2200 anos, após o retorno da linha costeira marinha à sua posição atual.

Em 2013, foram discutidas várias abordagens usando sensoriamento remoto e modelagem que poderiam simular as respostas dos manguezais à ENMM (BEZERRA, AMARAL e KAMPEL, 2013).

Mais recentemente, em 2016, uma pesquisa (FRANÇA et al., 2016) combinou dados geomorfológicos, sedimentológicos, paleontológicos e isotópicos para analisar a dinâmica dos manguezais no Sudeste do Brasil no contexto das mudanças climáticas. Eles identificaram vários ciclos em que as florestas de mangue holocênico foram substituídas por planícies de maré, após o declínio do nível do mar. Eles também concluíram que os manguezais existentes se desenvolveram nos últimos 900 anos, seguindo uma ENMM relativa.

Por fim, uma pesquisa realizada em 2017 (FONTES et al., 2017) também analisou dados geomorfológicos, sedimentológicos, paleontológicos e de sedimentos de manguezais para avaliar a compatibilidade entre as curvas de nível relativo do mar propostas para a dinâmica brasileira do litoral e do manguezal ao longo do vale fluvial do rio Jucuruçu (costa leste central do Brasil). Seus resultados indicam a ausência de manguezais durante o período holocênico, que ocorreu há cerca de 5.350 anos atrás.

Embora alguns desses estudos relacionando mudanças no nível do mar e a

dinâmica dos manguezais no Brasil tenham usado ferramentas e técnicas de sensoriamento remoto e/ou modelagem, nenhum deles tentou prever os impactos da mudança projetada do clima e do nível do mar nesses ecossistemas.

O objetivo do presente estudo é simular a resposta dos manguezais da costa oeste da Amazônia legal ao aumento do nível do mar e produzir uma avaliação de vulnerabilidade para este trecho da costa brasileira.

2 Área de Estudo

O Brasil possui a segunda maior cobertura de manguezais do mundo (13.400 km²), representando 8,5% do total mundial e 50% dos manguezais da América do Sul (SPALDING, KAINUMA e OLLINS, 2010). Cerca de 57% da área de manguezais do Brasil são encontradas no litoral norte, na parte oriental da costa da Amazônia legal e é dominado por um extenso complexo de sistemas de deltas. Essa área abrange mais de 7.000 km² e forma o maior sistema contínuo de manguezais do mundo (NASCIMENTO et al., 2013; SOUZA-FILHO, 2005).

Nessa região, o litoral é bastante recortado, com numerosas e longas penínsulas, com até 10 km de largura e estendendo-se por cerca de 30 km até o mar (NASCIMENTO et al., 2013). Uma combinação de padrões de corrente marítima e de depósito de sedimentos de vários rios (incluindo o rio Amazonas) produz um ecossistema de mangue altamente dinâmico.

Este estudo foca apenas a porção da costa oriental da Amazônia legal dentro do estado do Maranhão, região conhecida como Área de Proteção Ambiental das Reentrâncias Maranhenses (Fig. 1). Esta região foi transformada em uma Área de Proteção Ambiental em 1991 pelo governo brasileiro devido à ocorrência expressiva de manguezais. Devido à sua significativa importância ambiental em 1993, a APA das Reentrâncias Maranhenses também foi classificada como um sítio Ramsar (área úmida de interesse internacional), através do Decreto Estadual 11.901/91.

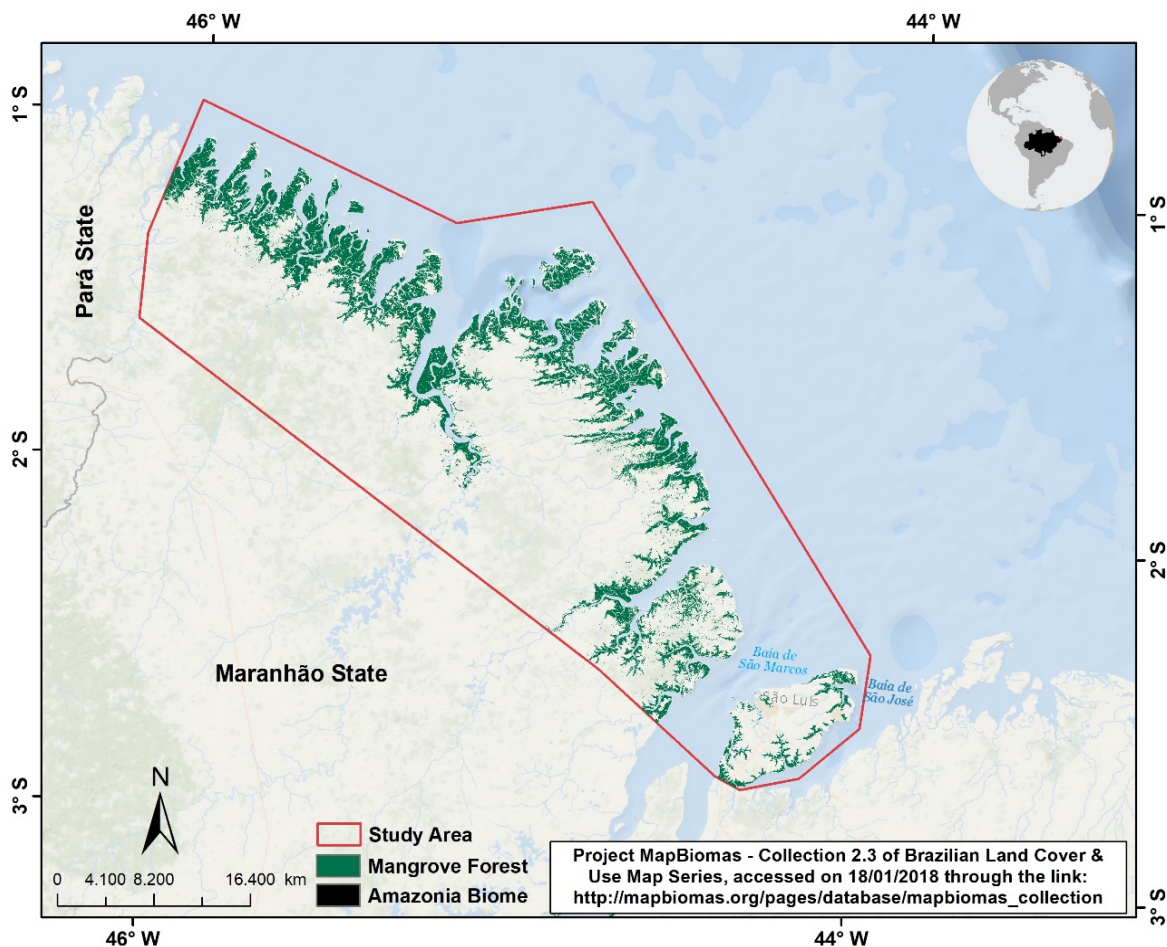


Figura 1. Área de Estudo: Costa oriental da Amazônia Legal inserida no Maranhão.

2.1 Clima

As características meteorológicas e oceanográficas da costa oriental da Amazônia Legal inserida no Maranhão são bastante distintas em comparação com outras regiões costeiras do Brasil. O clima é caracterizado por estações sazonais bem definidas, a estação seca (setembro-novembro) e a estação chuvosa (fevereiro-abril), período em que ocorre 73% da precipitação anual. As temperaturas médias do ar são geralmente acima de 25°C, com pouca variação entre as estações, e a precipitação anual varia de 2300 a 2800 mm (MORAES et al., 2005).

2.2 Estimativas da ENMM para a costa brasileira

O Painel Brasileiro sobre Mudanças Climáticas (PBMC) é a instituição oficial sobre mudanças climáticas (<http://www.pbmc.coppe.ufrj.br>).

Em 2017, o PBMC divulgou um relatório chamado “Impactos, vulnerabilidade e adaptação das cidades costeiras brasileiras às mudanças climáticas” (Disponível em:

<http://www.pbmc.coppe.ufrj.br/pt/publicacoes/relatorios-especiais-pbmc/item/relatorio-de-zonas-costeiras?categoryid=19>).

Neste relatório, o PBMC indica que não há séries históricas contínuas e informações confiáveis sobre a elevação do mar na costa brasileira, e há poucos estudos de modelagem de projeções de ENMM, o que prejudica qualquer previsão futura de aumento do nível do mar no Brasil. No entanto, existem algumas observações regionais para as taxas de elevação do mar em algumas cidades costeiras do Brasil que mostram taxas anuais de elevação variando de 0,002 a 0,0126 m entre meados do século XX e início do século XXI, como pode ser visto na Tabela 1.

Tabela 1. Mudanças no nível médio do mar ao longo da costa brasileira. Adaptado de PBMC (2017).

Autor	Cidades	Taxas de Variação (m/ano¹)	Período
Pirazolli (1986)	Recife (PE)	0,0037	1950 a 1970
	Salvador (BA)	0,0016	
	Canaveiras (BA)	0,0031	
	Imbituba (SC)	0,00055	
Aubrey et al., (1988)	Fortaleza (CE)	0,00003	1950 a 1970
	Belém (PA)	0,0034	
	Recife (PE)	0,00002	
	Salvador (BA)	0,0027	
	Canaveiras (BA)	0,0041	
	Rio de Janeiro (RJ)	0,0036	
	Imbituba (SC)	0,0007	
Silva (1992)	Rio de Janeiro	0,0126	1965 a 1986
Harari e Camargo (1994)	Recife (PE)	0,0056	1946 a 1988
França (2000) e Mesquita (2003)	Atlântico Equatorial	0,004	Dado altimétrico
Lasada et al., (2013)	Salvador (BA)	0,002	1950 a 2009
Médias observada (m/ano¹)		0,00318	

Adaptado do PBMC (2017)

2.3 Dinâmica de macromarés na costa oriental da Amazônia Legal

As marés nesta região variam em média em torno de 3,3 m da plataforma continental, porém podem ocorrer amplificações significativas das marés dentro dos estuários e baías. A amplitude das marés na Baía de Marajó (Pará/Brasil) é

de cerca de 4,0 m, enquanto na Baía de São José (Estado do Maranhão/Brasil) pode chegar a 7,5 m (DHN, 2017). A amplitude de maré é assimétrica (marés com elevação mais curtas), mas exibe uma queda acentuada das taxas de elevação cerca de 2 horas antes das marés altas, quando áreas extensas são inundadas (SOUZA-FILHO, 2005). Esse padrão de assimetria de maré pode impulsionar fluxos de vazante mais fortes, como indicado em estuários de macromarés semelhantes (LESSA, 2000).

Na área de estudo, a APA das reentrâncias Maranhenses (ver Fig. 1) há quatro eventos de maré em 24 h (dois eventos de maré baixa e dois eventos de maré alta). Nesta área, eventos de maré baixa variam de 0 a 4 m e os eventos de maré alta são geralmente superiores a 5 m. Para exemplificar, a figura 2 demonstra o padrão de ocorrência de eventos de baixa-mar e marés altas para o ano de 2017 em São Luís, Maranhão (BRA), os dados utilizados são provenientes do Centro Hidrográfico da Marinha do Brasil (para acessar os dados: <https://www.marinha.mil.br/chm/dados-do-segnav/dados-de-mare-mapa>).

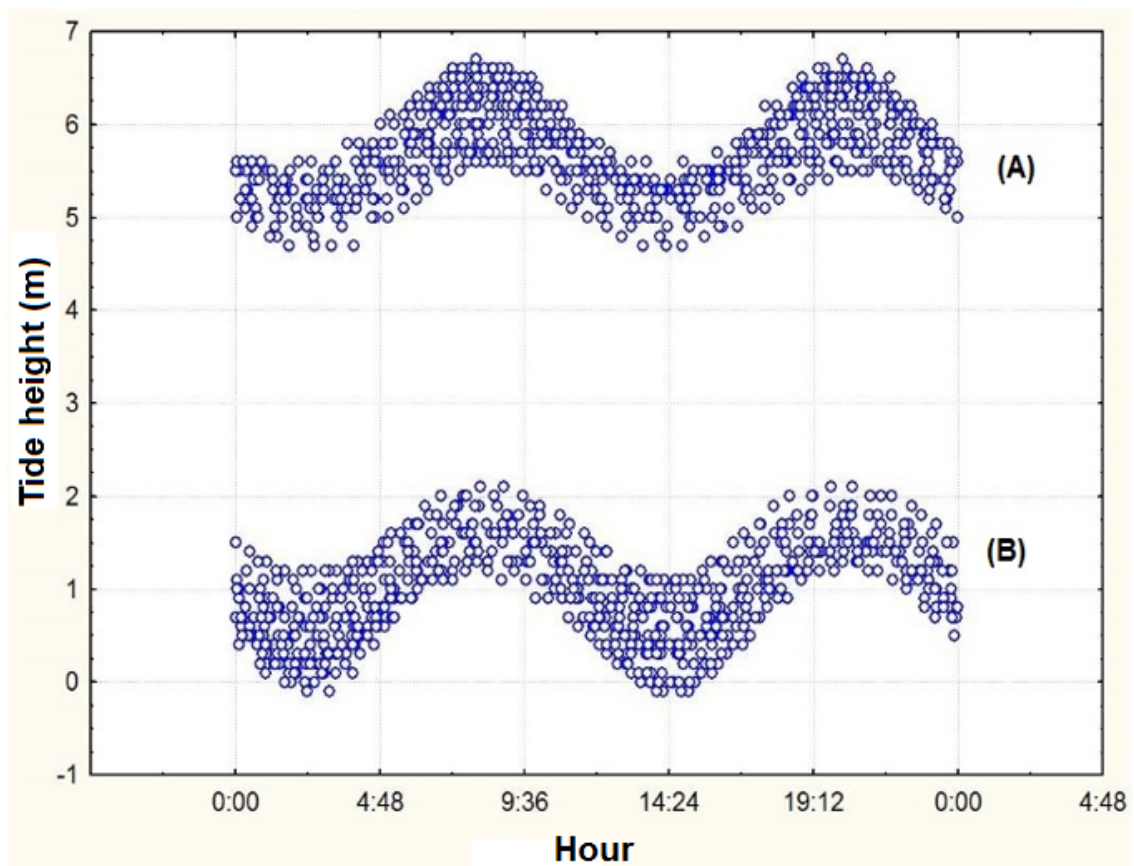


Figura 2. Variação da maré no Porto do Itaqui (São Luís, MA - Brasil) para o ano de 2017. (A) - Eventos de maré alta. (B) - Eventos de baixa maré.

3 METODOLOGIA

3.1 Modelo Experimental (BR-Mangue)

O modelo experimental utilizado foi o BR-Mangue e foi elaborado de acordo com os preceitos teóricos descritos por Bezerra (2014) que objetivou simular os impactos da ENMM em manguezais através de um modelo computacional. O modelo simulou a ENMM para a área de estudo em 90 (noventa) etapas de elevação, de 0,00318 m até 0,2862 m, com uma taxa anual de elevação de 0,00318 m para o período do ano de 2010 até 2100.

A taxa de elevação adotada para o presente estudo foi de 3,18 mm/ano (0,0318 m/ano), este valor corresponde aos valores médios de elevação do mar observados em algumas cidades brasileiras de acordo com o PBMC (ver tabela1).

Para o processo de elevação do nível do mar foi-se simulado um cenário de elevação do nível do mar até 0,2868 m, distribuído através de uma progressão aritmética na razão de 0,00318 m ("i") com 90 fases de elevação intermediárias, como demonstrado na Equação (1):

$$ENMM = ca + (taxa \text{ de elevação} \times i) \quad (\text{Equação 1})$$

Onde:

ENMM: é o valor do aumento do nível do mar em cada célula de água para a atual "taxa de elevação".

ca: é o valor da elevação na coluna de água (em metros) atual em cada célula de água;

taxa de elevação: corresponde ao intervalo de tempo necessário para a elevação do nível do mar. Considera-se que cada etapa de elevação é equivalente a um ano;

i: é uma constante relacionada ao aumento do nível do mar, cujo valor é 0,00318 m / taxa de elevação x ano.

O fluxo de água (Fluxo) corresponde ao deslocamento de água que ocorre de uma célula para outra, este processo se origina de uma célula de água para as células vizinhas e que pode ser de qualquer classe de cobertura (célula de mangue, célula desenvolvida, célula de vegetação terrestre e célula de outros

usos) que tem o valor de altitude menor que a elevação do nível do mar, conforme expresso na Equação (2):

$$\text{Fluxo} = \text{elevação do nível do mar} / \text{células vizinhas} \quad \text{Equação (2)}$$

Onde:

Fluxo: corresponde ao valor de “elevação do nível do mar” dividido pelo número de células vizinhas que fora preenchidas por água.

A ENMM pode modificar os padrões de sedimentação do material transportado pela coluna de água em ambientes estuarinos (COHEN e LARA, 2003). Para a simulação da acreção vertical dos bancos de lama que podem ser colonizados pelo manguezal, foi-se utilizada a Equação (3) estimada por Alongi (2008).

$$Y = 1.693 + 0.939x \quad \text{Equação (3)}$$

Onde:

Y: valores de acreção vertical do sedimento (mm).

X: valores de ENMM (mm).

Procedimentos de modelagem foram realizados para simular os seguintes eventos: (i) avanço da ENMM sobre o continente; (ii) deslocamento da área de influência das marés (DAIM); (iii) acúmulo longitudinal de sedimentos (formação de novos bancos de lama) em áreas adjacentes aos manguezais; (iv) mudanças na extensão das áreas de mangue e/ou nos manguezais resistentes à ENMM; (v) impacto dos obstáculos à migração do manguezal no continente para o desenvolvimento de novas áreas de manguezal.

Descrição das variáveis presentes no modelo BR-Mangue:

- **Área de mangue original** - corresponde à extensão de manguezal existente em 2010.

- **Redução das áreas de Manguezais** - corresponde à área de floresta de mangue que é suprimida em cada nível de ENMM;

- **Incremento das áreas de manguezais** - corresponde às áreas de manguezais jovens que conseguem migrar em cada evento de deslocamento

da área sob influência da maré (AIM);

- **Área remanescente de manguezal** - corresponde às áreas originais de manguezal que não são afetadas pelo aumento da coluna de água ou pelas áreas de manguezal que não são afetadas pela ENMM devido às altas taxas de sedimentação (horizontal e vertical).

O modelo computacional foi implementado na plataforma de modelagem denominada TerraME, um ambiente computacional de ferramentas para modelagem espacialmente explícita integrada com bancos de dados geospaciais. O TerraME suporta autômatos celulares, modelos baseados em variáveis dinâmicas e execução das variáveis em espaços de células 2D. O TerraME fornece uma interface para o banco de dados geográficos TerraLib, permitindo aos modelos acesso direto aos dados geospaciais. Sua linguagem de modelagem possui funções integradas que facilitam o desenvolvimento de modelos multi-escala e multi-variável para aplicações ambientais (mais informações em (<http://www.terrame.org/doku.php>)).

A implementação do BR-Mangue foi baseada no modelo computacional de autômatos celulares, um sistema lógico que tem o conceito de célula como unidade básica: cada célula possui uma vizinhança de células em um estado inicial que pode variar durante a simulação, conforme suas regras de transição (WOLFRAM, 1983).

3.2 Banco de dados e espaço celular

A base de dados geográficos e o espaço celular (Figura 3) foram criados em um sistema de informações geográficas desenvolvido pelo Instituto Nacional de Pesquisas Espaciais (INPE), o Terra View 4.2.0 (disponível em <http://www.dpi.inpe.br/terraview>) com projeção/datum: LatLong/WGS84. Foi adotada a resolução espacial de 1 km² (1 km x 1 km) e a área de estudo foi representada por um espaço celular contendo 20603 células (Figura 3A). Como um sistema de autômatos celulares, cada célula possui em um determinado momento, um estado único e um conjunto de atributos que define esse estado.

Durante os procedimentos de simulação, os estados e atributos de cada célula podem mudar de acordo com as regras de transição. O estado inicial da célula corresponde às classes de cobertura (floresta de mangue, água, vegetação terrestre, áreas desenvolvidas e outras) para o ano de 2010 (Figura 3B), e os atributos correspondem às classes de solos e altimetria (Figuras 3C e 3D, respectivamente). Os dados utilizados para os estados e atributos provêm do mapeamento oficial realizado pela Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA), e estão disponíveis no site de Zoneamento Ecológico e Econômico (ZEE) do Estado do Maranhão.

(<https://www.cnpm.embrapa.br/projetos/macrozee/>).

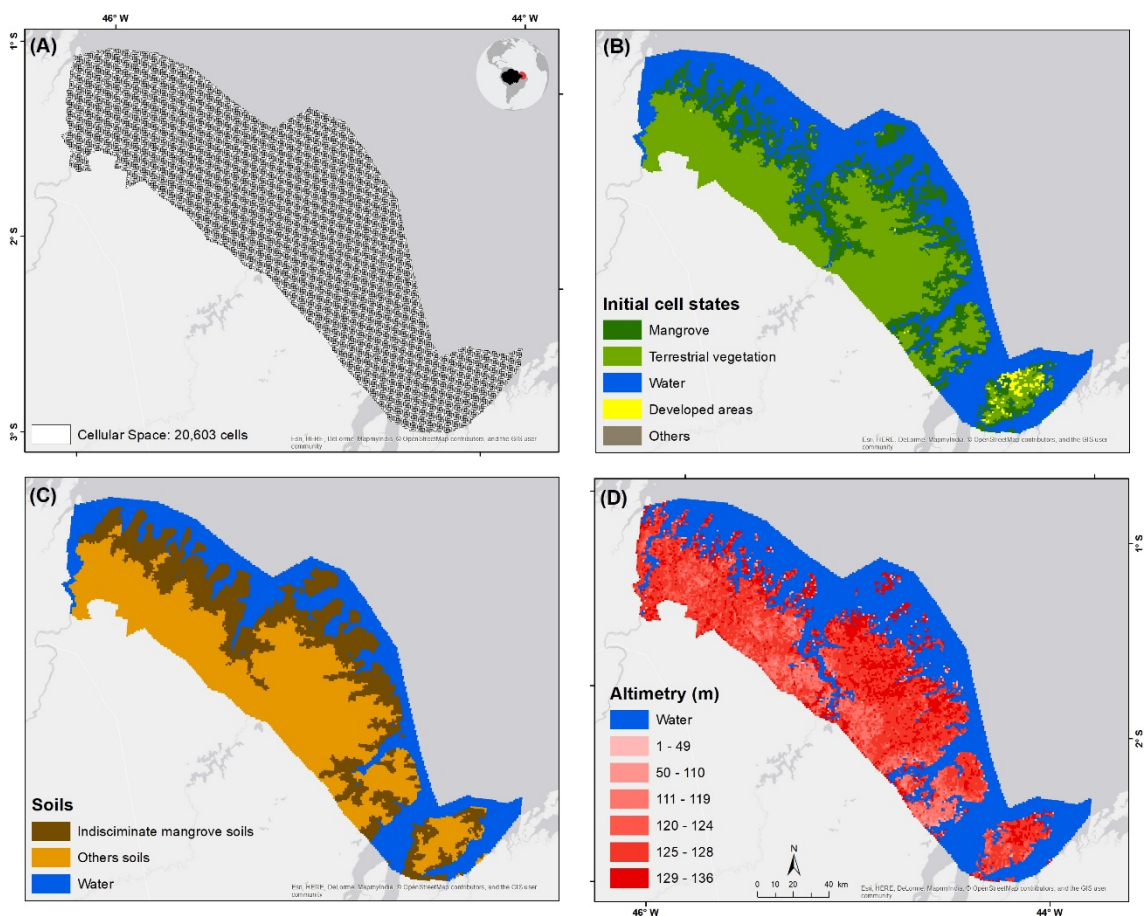


Figura 3. (A) Espaço celular vazio; (B) Estado inicial da célula; (C) Atributo do solo das células; (D) Atributo de altimetria das células.

Inicialmente, o espaço celular se encontra vazio, sem informações geográficas no banco de dados. Para preencher as células com valores de atributos, usamos o plug-in 'Fill cells' no software TerraView. O plug-in 'Fill Cells' permite o cálculo de valores de atributos de tabelas associadas a camadas de tipos de células.

O objetivo é padronizar informações de várias fontes, em diferentes formatos (dados vetoriais e raster, além de outras camadas celulares), agregando-os na mesma base espaço-temporal. Permite que os atributos de tabelas dinâmicas e estáticas sejam calculados. Dependendo da representação geométrica e da semântica dos atributos de dados de entrada, diferentes operadores podem ser aplicados. Foi-se utilizado o operador "classe majoritária".

O espaço celular é sobreposto aos arquivos com informações geográficas, e cada célula assume a informação geográfica que ocupa a maior parte da área da célula. Este procedimento foi utilizado para determinar os estados iniciais das células e seus atributos de solo e altimetria. Para o atributo de altimetria, o valor final da célula foi a média calculada de todos os valores de altimetria dentro de cada célula.

3.3 Regras de transição BR-Mangue (calibração).

A seguintes regras de transição para calibração do modelo foram usadas:

1. Os manguezais só existem na área sob influência das marés (AIM) (FARACO, ANGRETO-FILHO e LANA, 2010; FIELD, 1995; SPALDING, KAINUMA e COLLINS,2010)
2. A AIM é determinada pela amplitude das marés na área de estudo, isto é, entre eventos de baixa e alta maré;
3. Inicialmente, o valor da AIM varia de 2 a 5 m acima do nível médio do mar, conforme indicado por Ferreira (1988) e validado por dados de maré da base de dados oceanográficos da Marinha do Brasil (ver Figura 2). À medida que o nível do mar aumenta, o valor da AIM é atualizado pela adição dos incrementos do nível do mar calculados pelo modelo;
4. A cada etapa de elevação do nível do mar, as células de mangue podem migrar para células adjacentes, uma vez que barreiras naturais ou artificiais para migração de manguezais não estão presentes na AIM. Neste caso, as células da classe de cobertura da terra atribuídas como vegetação terrestre são convertidas em células de mangue;
5. Células de classe de cobertura de terra firme designadas como células de área desenvolvida correspondem a barreiras artificiais para migração de manguezais. Por outro lado, as barreiras naturais correspondem a células em

que o valor do atributo altimetria é maior do que o da AIM, ou o atributo do solo é diferente do “solo de mangue indiscriminado”

6. A inundação do mangue ocorre quando a altura da coluna d'água é maior ou igual à altimetria das células de mangue adjacentes. Neste caso, as células de mangue mudam para as células de água (inundação da célula de mangue);

7. Células classificadas como "área desenvolvida" ou "vegetação terrestre" podem ser inundadas pelo aumento do nível do mar. Neste caso, a inundação ocorre quando a altura da coluna d'água é maior ou igual à altimetria das células adjacentes.

4 Capítulo I: Artigo Submetido na Revista Estuaries and Coasts

PREDICTING THE IMPACTS OF SEA-LEVEL RISE ON THE AMAZON MACROTIDAL MANGROVE COAST

ABSTRACT

Brazil has the largest continuous area of mangrove forests in the world, the Amazon Macrotidal Mangrove Coast (AMMC). The objective of the present study is to simulate the response of eastern Amazonian mangroves to sea-level rise, and to produce a vulnerability assessment for this section of the Brazilian coast. We used a spatially explicit model, based on cellular automata and Geographic Information System (GIS) to identify resistance patterns, migration and/or inundation of these mangroves for different events of sea-level rise (SLR). The simulation considers 90 elevation events from 0.00318 m to 0.2862 m according to an arithmetic progression of reason 0.00318 m for the time interval from 2010 to 2100. The adopted SLR rate was 3.18 mm / year (0.00318 m / year), this rate corresponds to an average of sea elevation values observed for the Brazilian coast during the mid-twentieth century and early twenty-first century. At the end of the simulation (year 2100), the original mangrove area (4,180 km²) was reduced to 2,916 km², representing a loss of 30.24%. Our simulation also showed significant landward migration of the mangroves, and the modeled loss of the original mangrove area was compensated by a net addition of 301 km² of new mangroves inland, a net increase of 7.2% in the total mangrove area (4,481 km² in 2100). These results suggest that mangrove forests in the AMMC can present a pattern of area increase and migration to the continent from the projected SLR. These findings can help the identification of migration corridors for the Amazonian mangroves and the development of adaptation strategies in face of impending SLR.

Keywords: Mangrove forests, Amazonian coast, Climate change, Sea-Level Rise, Computational modeling, Geographic Information System.

Introduction

Mangroves function as a link between marine and terrestrial ecosystems, playing a vital role in the conservation of biological diversity in tropical and subtropical latitudes (Rog, Clarke and Cook, 2017). They possess highly developed morphological and physiological adaptations, which allow them to exist in conditions of high salinity, extreme tides, strong winds, high temperatures, and muddy, anaerobic soils (Alongi, 2009).

Mangroves are also extremely productive ecosystems, home to a large variety of fish, crab, shrimp, and mollusk species (Manson et al., 2005). They also contribute significant quantities of organic matter to coastal ecosystems, and are considered sites of intense biogeochemical processing, potentially impacting the global elemental cycles of carbon and nitrogen (Buillon et al., 2008; Cohen and Lara, 2003).

In addition, the dense root systems of mangrove forests trap significant amounts of sediment, stabilizing coastlines and preventing erosion from waves and storms (Mazda, Volanski and Ridd, 2007). By filtering out sediments, mangroves also protect coral reefs and seagrass beds from being smothered (Gillis et al., 2014). Together, coral reefs, seagrass beds, and mangrove forests provide a number of ecosystem services, and are among the most valuable natural systems on the planet. The annual value of products and services provided by mangrove forests are estimated to range between \$200,000 and \$900,000 per km² (Wells, 2006).

The warming of the climate system, because of human activities, is unequivocal and unprecedented (IPCC, 2013). This warming is causing changes with widespread impacts on both human and natural systems, on all continents and across all oceans. In coastal regions, these impacts include flooding and shoreline erosion due to sea-level rise (Nicholls, 2004), the intensification of the hydrological cycle (Huntington 2006), and changes in the frequency and intensity of severe storm events (IPCC, 2013).

Of all the effects of climate change, a rising sea level is considered to be the main factor of vulnerability for mangrove forests (Field, 1995). For the present research, the concept of vulnerability adopted is that presented by IPCC (IPCC,

2013), namely: *vulnerability is the degree by which a system is likely or unable to cope with adverse effects of climate change, including climate variability and extremes.*

Brazil is home to the second largest total area and the largest continuous area of mangrove forests in the world (Spalding, Kainuma and Collins, 2010; Nascimento et al., 2013). Therefore, understanding the response of Brazilian mangroves to the potential impacts of climate change is a significant challenge.

It is almost impossible to gather this information using traditional field-based methods, since mangrove swamps are extremely difficult to access. Fortunately, remote sensing technology provides a promising alternative to solve this problem of accessibility (Green et al. 2000; Howard et al., 2015).

Over the last 20 years, remote sensing techniques have demonstrated a high potential to detect, identify, map, and monitor mangrove conditions and changes (see the reviews by Guo et al., 2017; Heumann 2011; Kuenzer 2011; Purnamasayangasukasih et al., 2016). Some examples exist of remote sensing being used exclusively for mapping the extent and distribution of Brazilian mangrove forests (Lacerda, Menezes and Molisani, 2007; Nascimento et al. 2013; Souza-Filho, 2005; Souza-Filho, 2009). Nevertheless, few studies have attempted to simulate the response of these mangroves to climate change.

In 2009 was proposed a conceptual model of the response of mangrove forests to a possible increase in relative mean sea level induced by global warming (Soares, 2009). According to this model, responses will depend on the rates of sea level rise, rates of sedimentation, the topography of the area, and the availability of suitable areas for mangrove migration landward.

In 2010 was formulated a methodology to estimate the degree of combined vulnerability of mangroves and fishing populations to the impacts of climate change in the Paranaguá Estuarine Complex, in southern Brazil. In 2011, a Brazilian study proposed using mangrove reforestation as a tool for protecting the Potiguar Basin (in NE Brazil) from widespread erosion and shoreline instability resulting from climate change and human activities (Dantas, Amaro and Costa, 2011).

In 2012, other Brazilian research analyzed pollen, diatoms, and stable isotopes in a sediment core from Ilha do Cardoso mangroves (SE Brazil) and

determined that mangrove development ceased after an erosive event associated to the post-glacial sea-level rise (SLR) in the region (Pessenda et al., 2012).

The mangrove forests existing today in the region developed over the last 2200 years, after the return of the marine coastal line to its current position. In 2013 was discussed multiple approaches using remote sensing and modeling that could simulate mangrove responses to SLR (Bezerra, Amaral and Kampel, 2013).

Most recently in 2016, a research (França et al., 2016) combined geomorphological, sedimentological, palynological, and isotope data to analyze the dynamics of mangrove forests in Southeastern Brazil within the context of millennial and secular climatic and sea-level changes. They identified multiple cycles in which Holocene mangrove forests were replaced by tidal flats, following the decline in sea level. They also concluded that the existing mangroves developed over the last 900 years, following a relative SLR.

Finally, a survey conducted in 2017 (Fontes et al., 2017) also integrated geomorphological, sedimentological, palynological, and stable isotopic data from mangrove sediment cores to evaluate the compatibility between the Holocene relative sea-level curves proposed for the Brazilian littoral and mangrove dynamics along the fluvial valley of the Jucuruçu River (central eastern coast of Brazil). Their results indicate the absence of mangroves during the Holocene high sea-level stand, which occurred about 5,350 years ago.

Although some of these studies relating sea-level changes and mangrove dynamics in Brazil have used remote sensing and/or modeling tools and techniques, none have attempted to predict the impacts of the projected climate and sea-level change on these ecosystems.

The objective of the present study is to simulate the response of eastern Amazonian mangroves to sea-level rise, and to produce a vulnerability assessment for this section of the Brazilian coast.

Study Area

Brazil has the second largest mangrove coverage in the world (13,400 km²), accounting for 8.5% of the world's total and 50% of South America's mangrove

forests (Spalding, Kainuma and Collins, 2010). The most extensive areas (about 57% of all mangroves in Brazil) are found in the northern coast, along an extensive, tide-dominated complex of deltaic systems, in the eastern sector of the Amazonian coast. This area, called the Amazon Macrotidal Mangrove Coast (AMMC), covers over 7,000 km², and form the largest contiguous mangrove system in the world (Nascimento et al. 2013; Souza-Filho, 2005).

In this region, the coastline is very jagged with numerous long peninsulas, up to 10 km wide and extending about 30 km out to sea (Nascimento et al., 2013). A combination of coastal current patterns and sediment discharge from numerous rivers (including the Amazon) produce a highly dynamic mangrove ecosystem.

This study focuses only on the portion of the AMMC within the Maranhão state, region known as environmental protection area of the Maranhão reentrances – EPA of the Maranhão reentrances (Fig. 1). Here, mangroves reach their maximum seaward development, with widths varying between 26-40 km. This section contains about 72% (5,414 km²) of the mangroves in the AMMC (Souza-Filho, 2005).

This region was transformed into an Environmental Protection Area in 1991 by the Brazilian government due to the occurrence of its expressive area of mangroves. Due to its significant environmental importance in 1993, the EPA of the Maranhão reentrances was also classified as a Ramsar site (wetland of international interest).

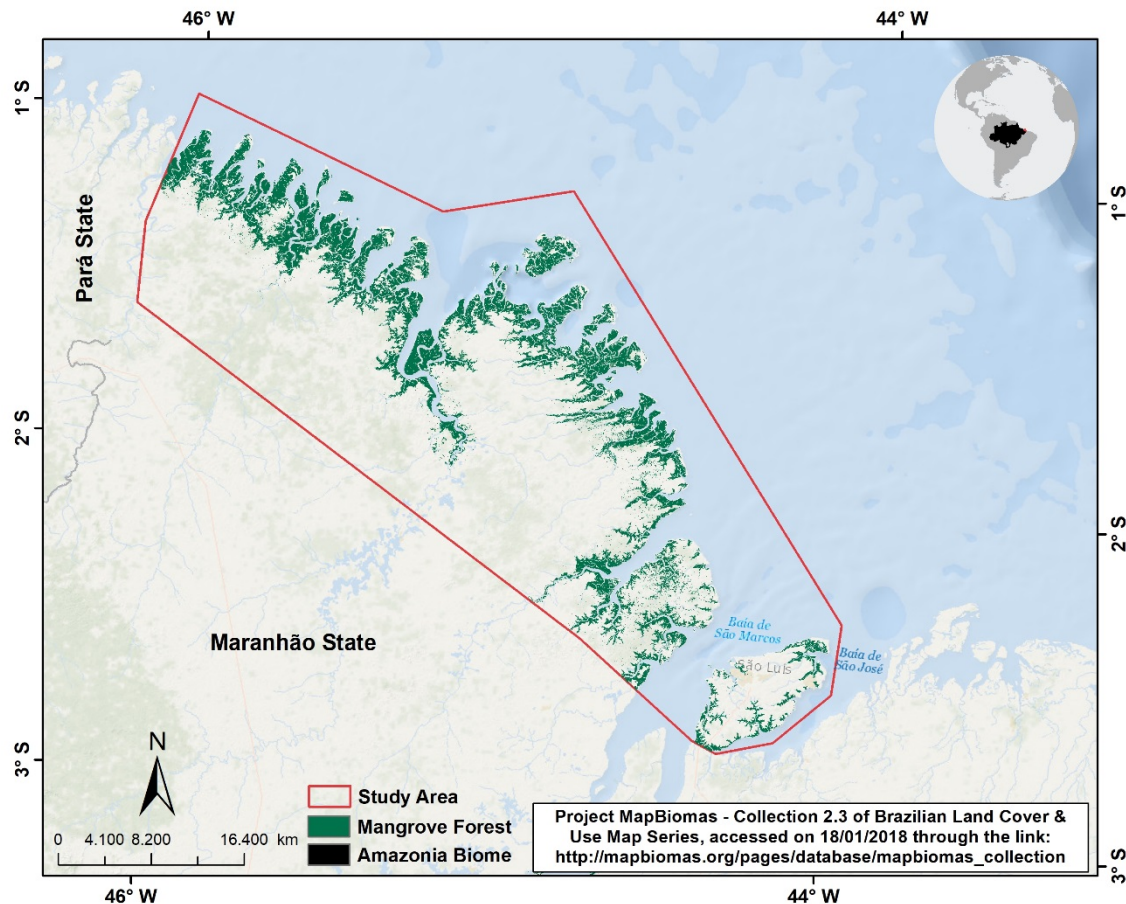


Figure 1. The study area comprises a section of the AMMC within the Maranhão state.

The meteorological and oceanographic characteristics of the AMMC are quite distinct in comparison with other coastal regions of Brazil. The climate is governed by seasonal changes in the position of the Inter-Tropical Convergence Zone (ITCZ), which is positioned around 14°N during the dry season (September-November) and around 2°S during the wet season (February-April), when 73% of the annual precipitation occurs⁵⁵. Average air temperatures are usually above 25°C, with little variation between seasons, and annual precipitation ranges from 2300-2800 mm (Moraes et al., 2005).

The continental platform extends some 330 km into the Atlantic Ocean, and receives the discharge of the Amazon River (16% of the World's freshwater discharge to the oceans) and dozens of other estuaries, which together supply over 1 billion tons of sediments, nutrients and organic material annually to the coastal zone (Martinelli et al., 1989). The outer shelf is dominated by carbonate sedimentation, both in the form of sand and reefs that have been dated at 17,000 years BP (Milliman and Barreto, 1075).

The inner shelf initiates approximately at the 20 m isobath (15 km away from the coast along the northeast of Pará State), where transgressive siliciclastic marine sands start to occur. The majority of the sand is composed of well-sorted clear quartz (Zembruscki 1971) and suggests a marine origin (Souza-Filho, 2005).

Estimates of Sea-level Rise for the Brazilian coast

In Brazil there is the Brazilian Panel on Climate Change (PBMC, in Portuguese), official Brazilian institution on climate change issues (for more information: <http://www.pbmc.coppe.ufrj.br/en/>). In 2017, PBCM released a special report “Impacts, vulnerability and adaptation of Brazilian coastal cities to climate change” (Available in: http://pbmc.coppe.ufrj.br/pt/publicacoes/relatorios-especiais-pbmc/item/relatorio-de-zonas-costeiras?category_id=19).

In this report, the PBMC indicates there is no continuous historical series and reliable information about sea elevation to the Brazilian coast, and there are few modeling studies of elevation projections, which undermines any future prediction of sea-level rise in Brazil. However, there are some regional observations for sea elevation rates in some coastal cities of Brazil that show annual rates of elevation varying from 0.002 to 0.0126 m between mid-twentieth century and early twenty-first century, as can be seen in Table 1.

Table 1. Changes in mean sea level along the Brazilian coast.

Author	Brazilian cities	Variation rates (m/year ¹)	Period
Pirazolli (1986)	Recife (PE)	0.0037	1950 a 1970
	Salvador (BA)	0.0016	
	Canaveiras (BA)	0.0031	
	Imbituba (SC)	0.00055	
Aubrey et al. (1988)	Fortaleza (CE)	0.00003	1950 a 1970
	Belém (PA)	0.0034	
	Recife (PE)	0.00002	
	Salvador (BA)	0.0027	
	Canaveiras (BA)	0.0041	
	Rio de Janeiro (RJ)	0.0036	
	Imbituba (SC)	0.0007	
Silva (1992)	Rio de Janeiro	0.0126	1965 a 1986
Harari e Camargo (1994)	Recife (PE)	0.0056	1946 a 1988
França (2000) and Mesquita (2003)	Atlântico Equatorial	0.004	Altimetric data
Lasada et al. (2013)	Salvador (BA)	0.002	1950 a 2009
Average of observations (m/year¹)		0.00318	

Adapted from PBMC (2017)

Dynamics of Macrotidal in AMMC

Tides in the region are semidiurnal, with mean spring tide ranging around 3.3 m on the inner shelf, although significant amplification occurs inside estuaries and bays. The tidal range in Marajó Bay (Pará State/Brazil) is around 4.0 m, while in São José Bay (Maranhão State/Brazil) it can reach 7.5 m (DHN 2017). The tide wave is asymmetrical (shorter rising tides), but displays a sharp decrease of rising rates about 2 hours before high spring tides, when extensive intertidal areas become inundated (Souza-Filho, 2005). This pattern of tidal asymmetry can drive stronger ebb flows, as indicated in similar macrotidal estuaries (Lessa 2000).

In the case study area, the environmental protection area of the Maranhão reentrances (see Fig. 1); there are 4 tidal events in 24 h (two low tide events and two high tide events). In this area, low tide events vary from 0 to 4 m and the events of high tides are usually above 5 m. To exemplify, the Fig. 2 demonstrates the pattern of occurrence of low tide events and high tides for the year 2017 for São Luís, Maranhão (BRA), the data used come from the Hydrographic Center of the Brazilian Navy (to access the data: <https://www.marinha.mil.br/chm/dados-do-segnav/dados-de-mare-mapa>).

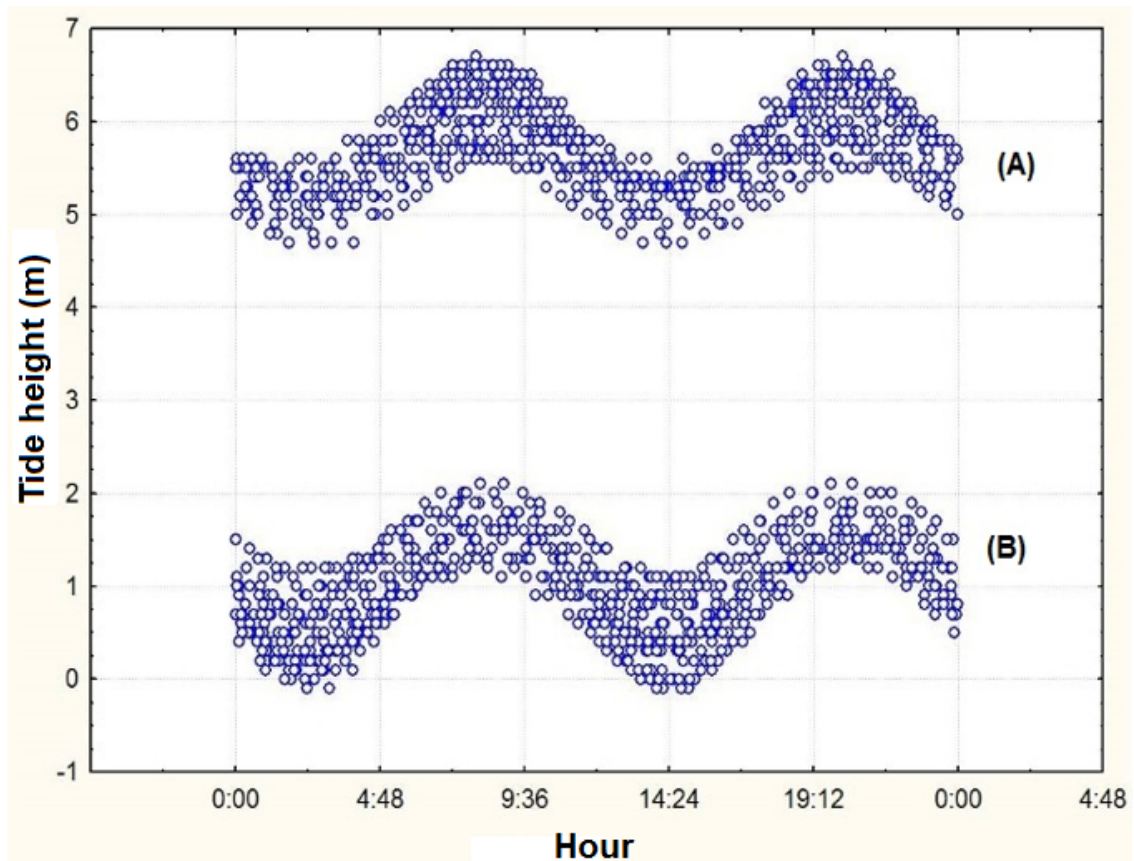


Figure 2. Variation of the tide in the Port of Itagui (São Luís, MA - Brazil)¹ for the year 2017. (A) - High tide events. (B) - Low tide events.

Modeling Experiment (BR-MANGROVE)

The model used in this paper (BR-MANGROVE) was prepared according to the theoretical precepts described by Brazilian research aimed at simulating the SLR impacts in mangrove (Bezerra et al., 2014), which developed a computer model to simulate mangrove ecosystem response to SLR. The model simulated the SLR for the study area in 90 (ninety) elevation steps, from 0.00318 m to 0.2862 m, with an annual rate of elevation of 0.00318 m from 2010 to 2100.

Elevation rate adopted for the present study was 3.18 mm/year (00318 m/year), this value corresponds to the average values of sea elevation observed in some Brazilian cities according to the PBMC (see Table 1).

The process of sea-level rise: we simulate a scenario of sea-level rise up to 0.2868 m, distributed as an arithmetic progression of reason 0.00318 m ("i") over 90 intermediate elevation steps, as demonstrated in the equation (1):

¹ Area belonging to AMMC.

$$(1) - \text{Sea-Level Rise} = \text{wc} + (\text{elevation step} \times i)$$

Where:

"Sea-level rise" is the value of sea-level rise in each water cell at current "elevation step";

"Elevation step" corresponds to the time step required for the sea-level rise. We consider that each elevation step is equivalent to one year;

"wc" is the value of water column (in meters) at current elevation step in each water cell; "i" is a constant related to the sea-level rise increment whose the value is 0.2868m/elevation step (year).

The water flux (Flux) corresponds to the displacement of water that occurs from a cell to another, this process originates from a water cell towards neighboring cells of any land cover class (mangrove cell, anthropic cell, terrestrial vegetation cell and beach cell) that have the altitude value lower than the sea-level rise, as expressed at equation (2):

$$(2) \text{ Flux} = \text{Sea-level rise} / \text{neighboring cells},$$

Where:

"Flux" corresponds to the value of "Sea-level rise" divided by the number of neighboring cells of each water cell.

The elevation of the sea can modify the sedimentation patterns of the material transported by the water column in estuarine environments (Cohen and Lara, 2003). For the simulation of vertical accretion of mud banks that can be colonized by the mangrove, we used equation (3) estimated by Alongi (2008).

$$(3) Y = 1.693 + 0.939x$$

Where:

- "Y" - values of vertical accretion of sediment in mm.
- "X" - SLR values in mm.

Modeling procedures were carried out in order to simulate the following events: (i) sea level advancement over the continent; (ii) displacement of the tidal influence area (TIA); (iii) sediment longitudinal accretion (formation of new mud banks) in areas adjacent to the mangrove forests; (iv) changes in the extent of the mangrove areas and/or the mangrove resists to SLR; (v) the impact of barriers to landward migration and the development of new mangrove areas. Below is a description of the elements in the BR-MANGROVE model:

- **Original mangrove area** - correspond to the existing mangrove extent in 2010 at the study area.
- **Mangrove Decrease** – correspond to the area of mangrove forest that is suppressed at each elevation step.
- **Mangrove increase** – correspond to the young mangrove areas that manage to migrate at each event of displacement of the TIA;
- **Remaining mangrove area** correspond to the original mangrove areas that are not affected by increased water column or the mangrove areas that are not affected by the SLR due to the high rates of sedimentation (horizontal and vertical).

The computational model was implemented using TerraME, a toolbox for spatially explicit modeling integrated with geospatial databases. TerraME supports cellular automata, agent-based models, and network models running in 2D cell spaces. TerraME provides an interface to the TerraLib geographical database, allowing models direct access to geospatial data. Its modelling language has built-in functions that makes it easier to develop multi-scale and multi-paradigm models for environmental applications (more information at <http://www.terrame.org/doku.php>).

Our implementation is based on the cellular automata computational model, a logical system that has the concept of cell as the basic unit: each cell has a neighborhood of cells and a discrete state that may vary during the simulation, according to its transition rules (Wolfram 1983).

Database and Cellular Space

The geographic database and cellular space (Fig. 3) were created in a geographic information system developed by the National Institute for Space Research (INPE), the TerraView 4.2.0 (available at <http://www.dpi.inpe.br/terraview/>), with projection/datum: LatLong/WGS84.

Adopting the spatial resolution of 1 km² (1 km x 1 km), the study site was represented by a cellular space containing 20,603 cells (Fig. 3A). As a cellular automata system, each cell has, at a certain time, a unique state and a set of attributes that defines this state. During the simulation procedures, the states and attributes of every cell can change according to the transition rules. The initial state of the cell corresponds to the land cover classes (mangrove forest, water, terrestrial vegetation, developed areas², and others) at the initial time for year 2010 (Fig. 3B), and the attributes correspond to the soils and altimetry classes (Figs. 3C and 3D, respectively).

The data used for the states and attributes comes from the official mapping conducted by the Brazilian Agricultural Research Corporation (EMBRAPA), and is available at the website of the Ecological-Economic Zoning of the Maranhão State (<https://www.cnpm.embrapa.br/projetos/macrozee/>).

² Areas occupied with human uses, where the original vegetation was removed.

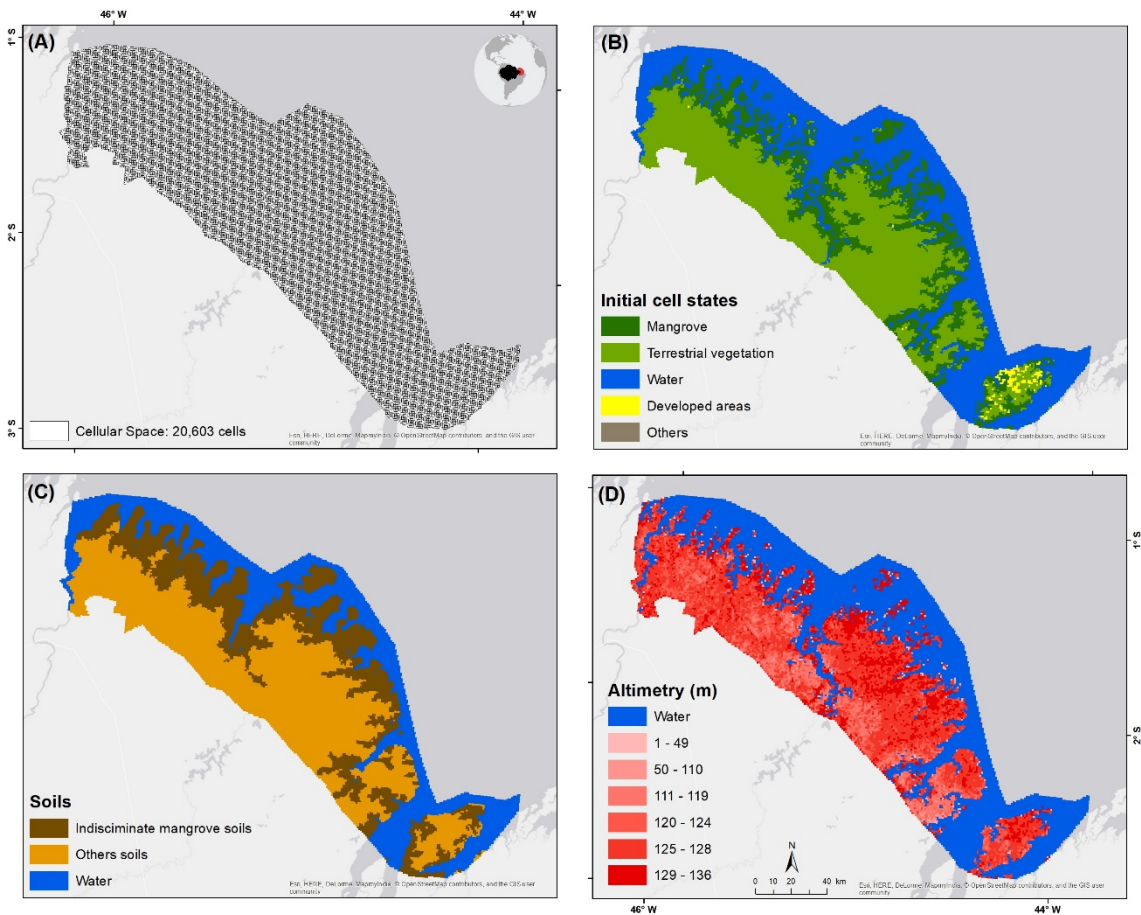


Figure 3. (A) Empty cellular space (B); Initial cell state; (C) Soil attribute of the cells; (D) Altimetry attribute of the cells.

Initially, the cellular space was empty, with no geographic information in the database. To fill the cells with attribute values, we used the ‘Fill cells’ plugin in the TerraView software. The ‘Fill Cells’ plugin allows the calculation of attribute values of tables associated with cell type layers.

The objective is to standardize information from various sources, in different formats (vector and raster data, in addition to other cell layers), by aggregating them in the same spatial-temporal base. It allows attributes from both dynamic and static tables to be calculated. Depending on the geometric representation and the semantics of the input data attributes, different operators can be applied. For this research, the ‘majority class’ operator was used.

The cellular space was superimposed on the files with geographic information, and each cell assumed the geographic information that occupied most of the cell area. This procedure was used to determine the cells initial

states and their soil and altimetry attributes. For the altimetry attribute, the final cell value was the calculated average of all altimetry values within each cell.

BR-MANGROVE rules transition (model calibration)

The following are the specific rules used for calibration of the model:

1. Mangrove only exists in the area under tidal influence (ATI) (Faraco, Angreto-Filho and Lana 2010; Field 1995; Spalding, Kainuma and Collins 2010);
2. The ATI is determined by the tidal range in the study area, that is, between low tide and high tide events;
3. Initially, the ATI value ranges from 2 to 5 m above the mean sea level, as indicated by Ferreira (1988) and validated by tide data from the oceanographic database of the Brazilian Navy (see Fig. 2). As sea-level rises, the value of ATI is updated by adding the sea level increments calculated by the model;
4. At every elevation step of sea-level rise, mangrove cells may migrate to adjacent cells since natural or artificial barriers for mangrove migration are not present on the ATI. In this case, cells of land cover class assigned as terrestrial vegetation are converted to mangrove cell (mangrove migration);
5. Cells of land cover class assigned as developed cells correspond to artificial barriers for mangrove migration. Conversely, natural barriers correspond to cells in which the altimetry attribute value is higher than the ATI, or the soil attribute is different than 'indiscriminate mangrove soil';
6. The mangrove inundation occurs when the height of the water column is greater than or equal to the altimetry of adjacent mangrove cells. In this case, mangrove cells change to water cells (mangrove inundation);
7. Cells classified as 'developed area' or 'terrestrial vegetation' can be inundated by the rising sea level. In this case, the inundation occurs when the height of the water column is greater than or equal to the altimetry of adjacent cells.

Result

This modelling exercise provides a vulnerability assessment of a portion of the eastern Amazonian mangrove forests to SLR, and their potential to migrate towards landward areas. Although we recognize the importance of other factors, such as changes to the local sedimentology and sediment supply (Gilman, Ellison and Coleman, 2007), changes in salinity resulting from hydrological adjustments to new water levels (Howard et al., 2015), and the species composition of the local mangrove forests (McKee, 2010), this vulnerability assessment is based solely on (1) sea-level rise relative to a static mangrove surface elevation, and (2) the existence of landward barriers, both natural and artificial.

In this study, the initial conditions for the model (corresponding to the year 2010) are: original mangrove, terrestrial vegetation, water, developed areas and bare soil. For this initial condition, the calculated mangrove area was 4,180 km², which corresponds to 20.3% of the study area (Fig. 4 A).

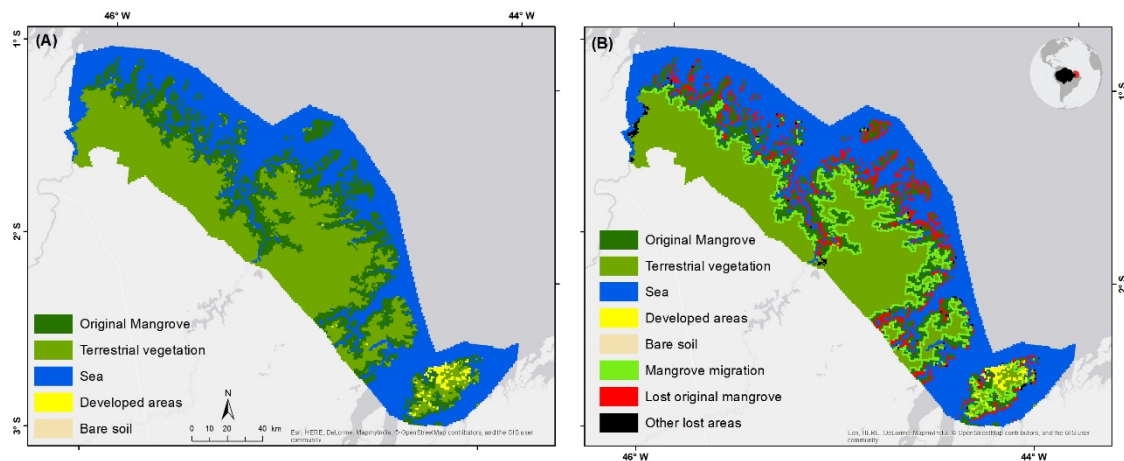


Figure 4. Initial condition for the modeling exercise in the study area (based on data for the year 2010).

At the end of the simulation (year 2100), the original mangrove area was reduced to 2,916 km², a loss of 30.24%, compared to the initial mangrove extent of 4,180 km². However, this loss of original mangrove area was compensated by extensive landward migration, which resulted in the addition of 1,585.4 km² of new mangrove cover, following the modeled SLR.

The study area presents favorable conditions for mangrove landward migration, since there are no significant anthropogenic barriers and no significant sediment inputs. In addition, the occurrence of macro-tides (with daily variations around 5 m) produces migration corridors along the many existing

stream channels, allowing mangroves to move upstream as sea level rises. Therefore, although the results of this modeling exercise indicate that there is a loss of the original mangrove area from the projected SLR, local conditions favors the expansion of new mangrove areas towards the continent (Fig. 4 B).

The total mangrove area at the end of the modeling exercise in 2100 presented a value of 4,481 km² (original mangrove areas minus mangrove area lost to inundation plus new mangrove area from landward migration), which, when compared to the original mangrove area, indicates an increment of 301 km² from the beginning to the end of the simulation. This corresponds to an increase in the total mangrove area of 7.2%, indicating that events of SLR can derive a positive impact on eastern Amazonian mangroves.

Discussion

The results of present study suggest that the Amazonian mangroves are very resilient, and their adaptive capacity to SLR appears to be large, as observed in similar tidal-dominated systems elsewhere (Alongi, 2009; Twilley and Day, 2012; Kirwan and Megonigal, 2013).

These mangroves are able to migrate vertically and horizontally, keeping pace with SLR by directly or indirectly influencing soil accretion processes through the production and accumulation of organic matter, as well as the trapping and retention of mineral sediment. Organic matter accumulation and its contribution to soil formation is widely recognized, and the processes controlling it has been well studied in many habitats.

A study showed that the relative contribution of organic solids to surface accretion in Caribbean mangroves was one to three times that of inorganic solids across study sites (McKee, 2010). This study also pointed to biological, rather than mineral controls on vertical accretion. Physical processes also contribute to mangrove vertical accretion, including inorganic sedimentation, groundwater influx (causing soil swelling) and deep land movements – such as geological uplift or glacial isostatic rebound (Krauss, McKee and Lovelock, 2014).

Landward migration has also been observed in other modeling studies. Alternative future sea-level rise and urbanization scenarios were used to map

landward migration of tidal saline wetlands along the Gulf of Mexico, and to identify locations where barriers may prevent such migration, and how existing protected lands might accommodate expected landward migration (Enwright, Griffith, Osland, 2016).

In Brazil, in the year 2014 was published the first Brazilian research aimed at simulating the SLR impacts in mangrove areas for the 21st century (Bezerra et al., 2014). The study focused on the Island of Maranhão, and the authors concluded that human occupation intensifies the negative impacts of the SLR, since they act as a barrier preventing the landward migration of the mangrove. In the AMMC was used radar data to map the dynamics of expansion and retraction in Amazonian mangrove forests (Nascimento et al., 2013). This research showed that, between 1996 and 2008, the mangrove experienced a loss of 14% (1212.50 km²) of original area, and an expansion of 22% (1931.04 km²) due to landward migration (Fig. 5), resulting in a net increase of the mangrove area of about 718.54 km², a 10.7% increase.

The authors suggest that a high sedimentation rate was the main factor responsible for the observed increase. The PBMC, in their 2013 report, indicate that, in addition to SLR, climate change can affect coastal dynamics and sedimentation rates, which may promote expansion of mangrove areas (PBMC, 2013).

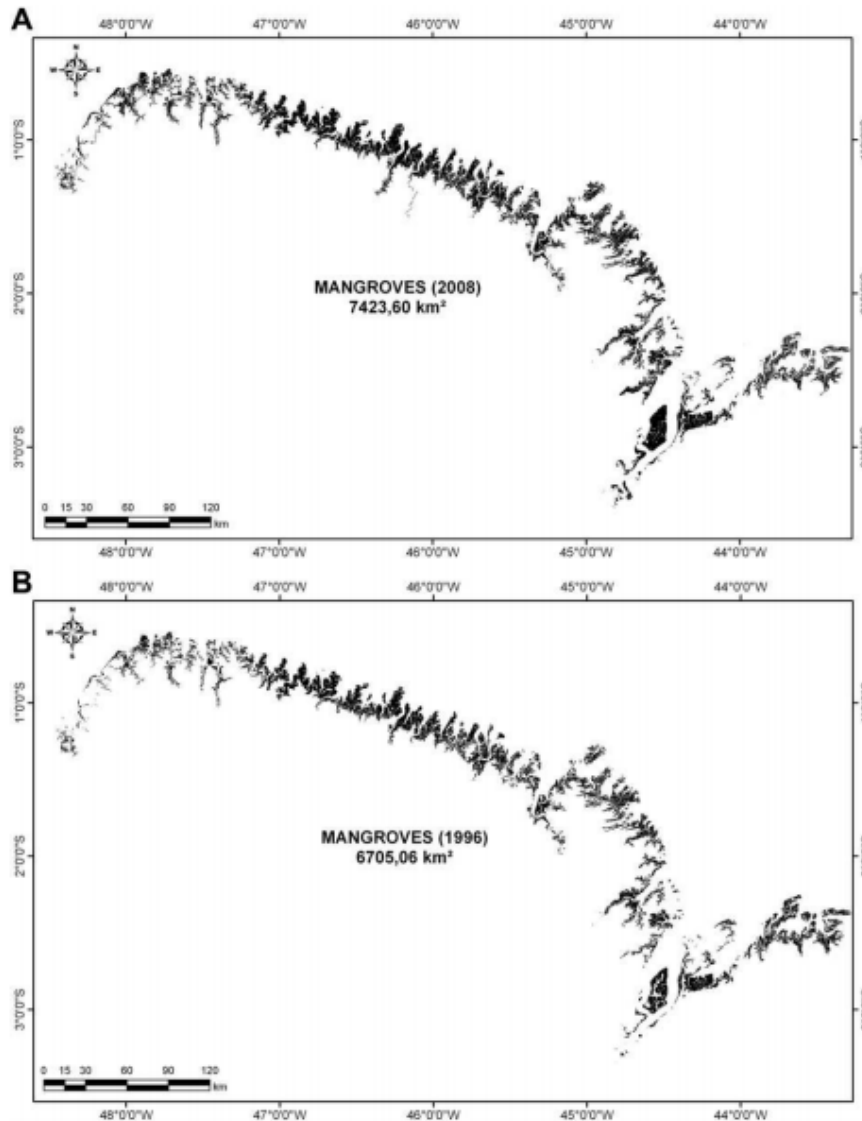


Figure 5. Changes in the extent of mangrove forests in the AMMC using radar data: (A) Mangrove area in 2008, (B) Mangrove area in 1996. Modified from Nascimento et al. (2013).

Other Brazilian researchers using robust methodological procedures for identifying changes in mangrove area coverage have observed similar patterns. For example, a study used a combination of GIS and remote sensing techniques to analyze a 25-year time series of radar and satellite images, aiming to identify changes in mangrove coverage along a section of the central Amazon coastline (Cohen and Lara 2003).

In this study was concluded that mangrove stands were migrating landward, possibly as a response to relative sea level rise, and that this migration was limited by local topography.

A literature review on the mangrove ecosystem response to climate change in the last 25 years and concluded that the mangroves of southeastern Brazil present patterns of expansion to the continent consistent with the sea-level rise impacts described in the scientific literature (Godoy and Lacerda, 2015; PBMC 2017). For example, studies indicate that some areas of mangroves in northeast Brazil showed an increase of 400% between 1993 and 2008.

Although SLR have been mentioned in these studies as a possible factor in the observed changes in mangrove area coverage, these authors point out to the peculiar coastal dynamics (erosion, progression, etc.) and to the influence of local land use and occupation as the main causes for the observed expansion/retraction patterns.

The uncertainty on the impacts of SLR in Brazilian mangroves results from the inexistence of an orthometric reference for the coastal zone, and the lack of historical sea level data that allows the establishment of specific rates of elevation for the Brazilian coast (Godoy and Lacerda, 2015).

Final considerations

The results presented here suggest that mangrove forests in the AMMC may present a pattern of migration to the continent and show a net gain of area (7.2% increase in mangrove area) for potential SLR events. These mangroves can use existing tidal channels to migrate landward into the continent, as sea level rises, and thus colonize areas of terrestrial vegetation or other areas that allow the colonization of the mangrove.

Another factor that corroborates the pattern of mangroves migration observed in the simulation is the small influence of human occupations in the AMMC, as well as, the presence of macrotides that can amplify the effects of SLR. Based on these findings, Brazilian public policies for preservation of areas adjacent to Amazonian mangroves should be intensified, focusing on the identification of migration corridors for the mangroves and the development of adaptation strategies in face of impending sea-level rise. In this context, new studies should be developed that identify areas with potential to be colonized by mangroves in different scenarios of SLR in the AMMC.

The Amazonian mangroves comprise the largest continuous area of mangroves in the world, and provide numerous environmental services to the coastal zone (nursery for marine life, a precious stock of blue carbon, and coastline protection to extreme climatic events). Therefore, it is vital to promote a better understanding of their response patterns to SLR events and other impacts of climate change, and to promote landscape-scale conservation plans that will enable these unique ecosystems to migrate both vertically and horizontally in response to future SLR.

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5 CONCLUSÕES

O presente estudo sugere que os manguezais da Amazônia oriental são muito resilientes e possuem alta capacidade de adaptação à ENMM, como observado em outros sistemas dominados por maré (ALONGI, 2009; TWILLEY e DAY, 2012; KIRWAN e MEGONIGAL, 2013). Esses manguezais são capazes de migrar vertical e horizontalmente em resposta à ENMM, influenciando direta ou indiretamente os processos de acúmulo do solo através da produção de matéria orgânica, bem como a retenção de sedimentos minerais. O acúmulo de matéria orgânica e sua contribuição para a formação do solo são amplamente reconhecidos, e os processos que o controlam foram bem estudados em muitos habitats.

Neste estudo concluiu-se que os manguezais estavam migrando para o interior, possivelmente como resposta à elevação do nível do mar, e que esta migração foi limitada pela topografia local.

Os resultados aqui apresentados sugerem que as florestas de mangue na área de estudo podem apresentar um padrão de migração para o continente e mostrar um ganho líquido de área (aumento de 7,2% na área de manguezal) para potenciais eventos ENMM.

Esses manguezais podem usar os fluxos de maré existentes para migrar para o continente, à medida que o nível do mar aumenta, colonizando assim áreas de vegetação terrestre ou outras áreas que permitem a colonização do manguezal. Outro fator que corrobora o padrão de migração dos manguezais observado na simulação é a pequena influência das ocupações humanas na zona costeira oriental da Amazônia Legal, bem como a presença de macromarés que podem ampliar os efeitos da ENMM.

Com base nesses resultados, as políticas públicas brasileiras de preservação de áreas adjacentes aos manguezais da Amazônia devem ser intensificadas, com foco na identificação de corredores de migração para os manguezais e no desenvolvimento de estratégias de adaptação frente à elevação iminente do nível do mar.

Neste contexto, novos estudos devem ser desenvolvidos para que sejam identificadas as áreas com potencial para serem colonizadas por manguezais

em diferentes cenários de ENMM.

Os manguezais da Amazônia compreendem a maior área contínua de manguezais do mundo e fornecem vários efeitos ambientais positivos para a zona costeira (berçário para a vida marinha, um estoque precioso de carbono azul e proteção costeira para eventos climáticos extremos).

Portanto, é vital promover uma melhor compreensão de seus padrões de resposta aos eventos da ENMM e outros impactos da mudança climática, e promover planos de conservação que permitirão que esses ecossistemas únicos migrem vertical e horizontalmente em resposta à futura ENMM.

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ANEXO: Normas para submissão na Revista

Estuaries and Coasts

GENERAL DESCRIPTION

Estuaries and Coasts is the journal of the Coastal and Estuarine Research Federation. Begun in 1977 as Chesapeake Science, the journal has gradually expanded its scope and circulation. Today, the journal publishes manuscripts on ecosystems at the interface between the land and the sea, covering aspects of research on physical, chemical, geological or biological systems, as well as applications to management of those ecosystems. The interface is broadly defined to include estuaries and nearshore coastal Waters including lagoons, wetlands, tidal rivers, shorelands and beaches. The journal publishes original research findings, reviews and perspectives, techniques, comments, and management applications. Submissions that are primarily descriptive, strongly place-based, or report on development of models or new methods without detailing their applications fall outside the scope of the journal.

All types of articles published in *Estuaries and Coasts* are peer reviewed by at least two reviewers prior to publication.

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TYPES OF ARTICLES

1. **Original Reports** of research results typically follow the structure of Title and Author Information, Abstract, Introduction (including research questions and hypotheses), Methods, Results, Discussion, and References.

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3. **Notes**, shorter reports of research results, follow the same structure as original reports of research and management applications.

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5. **Perspectives in Estuarine and Coastal Science** are short papers (maximum 8 printed pages) intended to stimulate discussion of emerging areas of estuarine and coastal research. A maximum of one such paper is published per journal issue (i.e., 6 per year). These papers are solicited by the Co-Editors-in-Chief or proposed to one of the Co-Editors-in-Chief through pre-submission inquiries by prospective authors. The Perspectives papers are published with free promotional access to the online version.

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Acknowledgments

Acknowledgments of people, grants, funds, etc. should be placed in a separate section on the title page.

The names of funding organizations should be written in full.

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- Negotiation research spans many disciplines (Thompson 1990).
- This result was later contradicted by Becker and Seligman (1996).

- This effect has been widely studied (Abbott 1991; Barakat et al. 1995; Kelso and Smith 1998; Medvec et al. 1999).

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Reference list entries should be alphabetized by the last names of the first author of each work.

- Journal article

Alber, John, Daniel C. O'Connell, and Sabine Kowal. 2002. Personal perspective in TV interviews. *Pragmatics* 12: 257–271.

- Article by DOI Suleiman, Camelia, Daniel C. O'Connell, and Sabine Kowal. 2002. 'If you and I, if we, in this later day, lose that sacred fire...': Perspective in political interviews. *Journal of Psycholinguistic Research*. doi: 10.1023/A:1015592129296

- Book Cameron, Deborah. 1985. *Feminism and linguistic theory*. New York: St. Martin's Press.

- Book chapter Cameron, Deborah. 1997. Theoretical debates in feminist linguistics: Questions of sex and gender. In *Gender and discourse*, ed. Ruth Wodak, 99-119. London: Sage Publications.

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