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Simulating Sea-Level Rise Impacts on Mangrove Ecosystem adjacent to Anthropic Areas: the case of Maranhão Island, Brazilian Northeast

DENILSON DA SILVA BEZERRA[1], SILVANA AMARAL[1], MILTON KAMPEL[1] & PEDRO RIBEIRO DE ANDRADE[1]

[1] National Institute for Space Research – INPE. Post Office Box 515 - 12227-010 - São José dos Campos - SP, Brazil. E-mail: denilson.bezerra@inpe.br

Abstract. Sea-level rise is one of the main effects of climate changes on coastal zones; mangroves are particularly sensitive to this process. In addition, intense human occupation hinders mangrove colonization of new areas. This paper proposes a methodological approach, using spatially explicit modeling based on cellular automata, to simulate impacts of sea-level rise on mangrove ecosystems. Initially, we present the conceptual model, the rules for interaction between model elements, and the methodological procedure for computational implementation. The model was applied simulating 10 elevation steps from 0.1 to 1 m on Maranhão Island which contains an extensive mangrove area and is densely occupied. The results are presented in the context of changes in mangrove areas (increase or reduction). The simulation showed that the mangrove area increased about 6.75% to 0.3 m of sea level rise. However, for values above 0.4 m, it showed a significant loss of area, indicating the complexity of its response to sea-level rise in anthropic areas. Our work suggests that modeling tools can be useful for the study of sea-level rise impacts on mangrove, especially in complex land cover areas such as the Brazilian coastal zone.

Keywords: climate change, coastal zone, spatially explicit modeling, cellular automata, elevation steps

Resumo. Simulando impactos da elevação do nível do mar no ecossistema manguezal adjacente a áreas antrópicas: o caso da Ilha do Maranhão, nordeste brasileiro. A elevação do nível do mar é um efeito típico das mudanças climáticas; o manguezal é particularmente sensível a este processo. A ocupação humana inviabiliza a colonização do manguezal em novas áreas. Este artigo propõe uma abordagem metodológica para simular os impactos da elevação do mar no manguezal, usando modelagem espacialmente explícita baseada em autômatos celulares. Inicialmente é apresentado o modelo conceitual, as regras para a interação entre os elementos e os procedimentos metodológicos para implementação computacional. A simulação considera 10 passos de elevação de 0.1 a 1 m na Ilha do Maranhão que contém extensa área de manguezal e é densamente ocupada. Os resultados são apresentados no contexto de alterações nas áreas de manguezal (aumento e redução). A simulação evidenciou que o mangue aumentou em cerca de 6,75% a 0,3 m de elevação. Contudo, para valores acima de 0,4 m, o manguezal apresentou uma expressiva perda de área, indicando a complexidade da resposta do manguezal a elevação do mar em áreas antropizadas. Os resultados obtidos sugerem que ferramentas de modelagem podem ser usadas para estudar os impactos da elevação do nível do mar no manguezal, principalmente em áreas de uso e ocupação complexos como na zona costeira brasileira.

Palavras-chave: mudança climática, zona costeira, modelagem espacialmente explicita, autômato celular, passos de elevação

Introduction

Mangrove is an environment of transition between the sea and the continent, this ecosystem plays a vital role in conserving biodiversity and buffering disturbance in coastal regions (Lugo *et al.* 2010). For the products and services offered by mangroves, it is estimated that annual monetary values range from US$ 200,000,000 to US$ 900,000,000 per km^2 (UNEP-WCMC 2006).

The distribution of mangroves in the Brazilian territory spreads from the Brazilian border with the French Guiana, just above the Equator line (04º 30' N), to the state of Santa Catarina (28º 30' S) (Schaeffer-Novelli *et al.* 2000). The largest continuous mangrove area of the planet is in the Brazilian Amazon (Souza-Filho 2005) with approximately 8,900 km^2 in length (Kjerfve *et al.* 2002). Brazil has 13,000 km^2 of mangroves, being the second country in total mangrove area (Spalding *et al.* 2010).

The process of anthropogenic warming of the climate system is likely to have probably initiated during the pre-industrial time (IPCC 2007). One typical effect of climate change is the phenomenon of sea-level rise; this process is irreversible for at least 1,000 years as a result of thermal expansion of the oceans (Solomon *et al.* 2009). According to the fourth assessment report of the Intergovernmental Panel on Climate Change (AR4-IPCC), sea level rise during the 20th century ranged from 0.12 m to 0.22 m (IPCC 2007), other projections indicate that sea-level rise might oscillate from 0.26 m to 0.59 m until the last decade of the 21st century (Solomon *et al.* 2007). More recent estimates indicate that the average rise in sea level can reach up to 1m by 2100 (Lowe *et al.* 2009).

Among the anticipated effects of climate change, sea-level rise is the primary factor for the modifications in mangrove environments (Field 1995, Lovelock & Ellison 2007). In response to the impacts of sea-level rise, mangrove ecosystems may suffer profound modifications, such as a decrease or an increase of the ecosystem areas, migration, loss of biological diversity, and changes in the supply of environmental products and services (McLeod & Salm 2006).

Land cover types associated to human presence may maximize the negative impacts of the process of sea-level rise on mangroves because human occupation usually impairs the mangrove colonization in new areas where sea-level rise occurs (Lovelock & Ellison 2007, Soares 2009, Faroco *et al.* 2010).

So far, in Brazil, there have been few studies of anthropic climate change impacts on mangrove ecosystems: Soares (2009) developed a conceptual model for mangrove response to sea-level rise and Faroco *et al.* (2010) analyzed the vulnerability to climate change for the social-ecological system in Brazilian mangroves.

Understanding the impacts of climate change on mangrove dynamics in Brazil is a great challenge once the Brazilian mangrove provides many products and services to the coastal zone. For example, Brazilian artisanal fishermen are highly dependent on mangrove resources and services (Faroco *et al.* 2010).

The use of computational models can help understand the response pattern of mangroves to climate change (Berger *et al.* 2008). This tool has been used to simulate the impacts of sea-level rise (Doyle *et al.* 2010) and hurricanes (Doyle 2003) on mangrove ecosystems.

This paper proposes the use of computational modeling approach based on cellular automata to simulate mangrove response to sea-level rise in anthropic areas. We propose a conceptual model, integrating land cover types, sea level dynamics, and biophysical conditions, implemented in a spatially explicit model. The model simulated the effects of sea-level rise on Maranhão Island, state of Maranhão, Brazil, where mangroves and anthropogenic activities dominate the landscape.

Since computational models can be used as an additional tool to understand and simulate impacts on mangrove environments (Berger *et al.,* 2008), our work aims to contribute to the development of further strategies for mitigation and adaptation of the effects of climate change on mangroves, especially for those adjacent to urban areas.

Conceptual Model

Mangrove responses to sea-level rise depend on factors such as topography, tidal range, land cover in adjacent areas, coastal dynamics and mean rate of sea-level rise (Mcleod & Salm 2006, Lovelock & Ellison 2007). In order to represent and simulate the impacts of sea-level rise on coastal zones, we propose a general conceptual model that stratifies the relevant aspects specific for the mangrove persistence in four components (Figure 1).

Sea-level rise reaches different land cover types in a geographical space. Each land cover type is considered as a barrier or potential area for mangrove migration, restricted by the environmental conditions for mangrove establishment.

The biophysical condition and adjacent land cover mosaic cause various impacts on mangrove dynamics: water column increase, displacement of the area over tidal influence, mangrove inundation, and mangrove migration to continent, as described in the literature (Scavia *et al*. 2002, Alongi 2008, Gilman *et al*. 2008).

This general framework supports further extensions, by adding other components that could include the influence of hydrology, climate or even oceanic circulation for mangrove dynamics, not

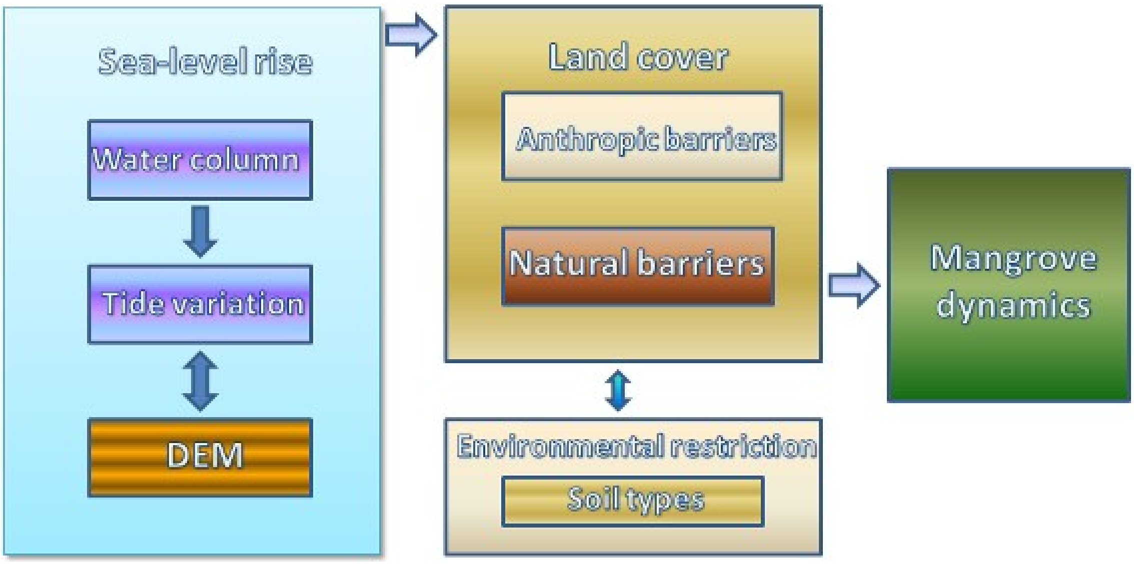

Figure 1. Diagram demonstrating the general conceptual model proposed to simulate the impacts of sea-level rise on mangrove areas.

addressed at this stage of our work. Any proposed components can become as complex as the theoretical subjacent assumptions. Each component of the actual conceptual model is a module for its implementation and has its particular assumptions.

In the Sea-level rise Module, the reference for the inundation process is the value of the water column in relation to the topography of adjacent areas, indicated by the Digital Elevation Model (DEM). When the sea advances toward the continent, mangrove and other land cover type areas may be inundated. We consider that a negative impact on mangrove: the inundation may reduce the mangrove area and may affect its ability to provide services to the coastal zone.

Tide height defines areas under tidal influence (Miranda *et al*. 2002) which are regions to where mangrove can progress. Sea-level rise can displace tidal influence, favoring the migration of mangroves (Ellison 1993, Schaeffer-Novelli Y *et al*. 2002; Gilman *et al*. 2008). This phenomenon can be considered a positive impact since it may promote the expansion of mangrove areas.

In the Land Cover Module, each land cover type can be considered either an anthropic barrier or prone to be converted to mangrove area. The process of migration can be rendered impossible due the presence of anthropic and natural barriers (Soares 2009, Faroco *et al*. 2010). Here, anthropic barriers are represented by areas where native vegetation has been removed and converted to impervious surfaces as result of human activities. Natural barriers are beaches as well as areas that are out of reach of tidal influence.

In the Environmental Restriction Module, at this stage, only soil type is considered. Mangroves grow on substrates with high silt and clay content, with high salinity levels, under strong tidal influence, and in conditions close to anoxia (McLeod & Salm 2006, Spalding et al. 2010). In general, specific soil type, as indiscriminate mangrove soils, holds ideal conditions for colonization by mangrove typical vegetation, whereas other soils (dystrophic yellow medium texture and podzolic red-yellow concretionary) are considered as barriers to mangrove occupation.

The Mangrove Dynamic Module describes the impacts resulted from the interactions between the sea-level rise over the terrain, the land cover pattern, and the environmental constraints. It will determine the conditions for mangrove persistence, migration or retraction, leading to different impacts on its service provisions, for a specific area.

Methods

The Modeling Environment

Based on the conceptual model, the computational model was implemented using a toolbox for spatially explicit modeling integrated with geospatial databases called TerraME[1] (Carneiro et al. 2013): a programming environment for spatial dynamical modeling, supporting cellular automata, agent-based models, and network models running in 2 D cellular spaces.

We used the language Lua, an open-source interpreted language with extensible semantics, to implement the model source code at TerraME (see supplementary material).

[1] Available at http://www.terrame.org

Our implementation is based on the cellular automata computational model, a logical system which 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).

Test Site

As a spatially explicit modeling procedure was used, Maranhão Island in the northeast of Brazil was chosen as test site. The island contains extensive mangrove areas of 17,387 ha (Rebelo-Mochel 2003) and is densely occupied, including the city of São Luis, the capital of Maranhão state with 1,014,837 inhabitants (IBGE, 2010).

Maranhão Island, also known as São Luís Island (Figure 2) is an archipelago with more than 50 islands of various sizes and origins, located on the northern coast of the state, in the Brazilian Amazon between 2º 24` 10”S and 2º 46` 37”S, and 44º 24` 30”W and 43º 59` 43”W . The coastline is deeply indented, with approximately 626 km of perimeter, along which the mangrove ecosystem is present in about 90% of it, covering 146,49 km2 (Rebelo-Mochel 2003). Another striking feature of Maranhão Island is the presence of macromareal that can vary from 6 to 7 m (Ferreira 1988).

The topography on Maranhão Island is gently undulated, with altitudes of up to 60 meters (Pereira & Zane 2007). It favors severe saltwater intrusion in rivers and forms extensive estuarine areas (Silva Junior et al. 2007).

The dynamics of the local marine intrusion influences the pedology of the study site, which is composed of three main soil classes: indiscriminate mangrove soils, yellow dystrophic medium texture soil, and red-yellow concretionary podzolic (UEMA 2000; EMBRAPA 2002).

The indiscriminate mangrove soils are very poorly drained areas, with high salinity from seawater and sulfur compounds, occurring in low sedimentary sites that are frequently flooded, and where the organic matter accumulates on the coast. These characteristics confer ideal conditions for colonization by typical mangrove vegetation on mangrove soils (UEMA 2000; EMBRAPA 2002, Rebelo-Mochel 2003).

Geographical Database and Cellular Space

For the model simulation procedure, a geographical database was organized at TerraView 4.2.0 geographical information system (INPE 2011). Adopting the spatial resolution of 1 ha (100 x 100 m), the study site was represented by a cellular space containing 94,704 cells (Figure 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 class at the initial time. For Maranhão Island, the mangrove mapping for the year 2008 done by the Brazilian Institute of Environment and Renewable Resources (IBAMA) was updated by visual interpretation of 2011 ETM/Landsat 5 images, keeping the original land cover classes (Figure 3b):

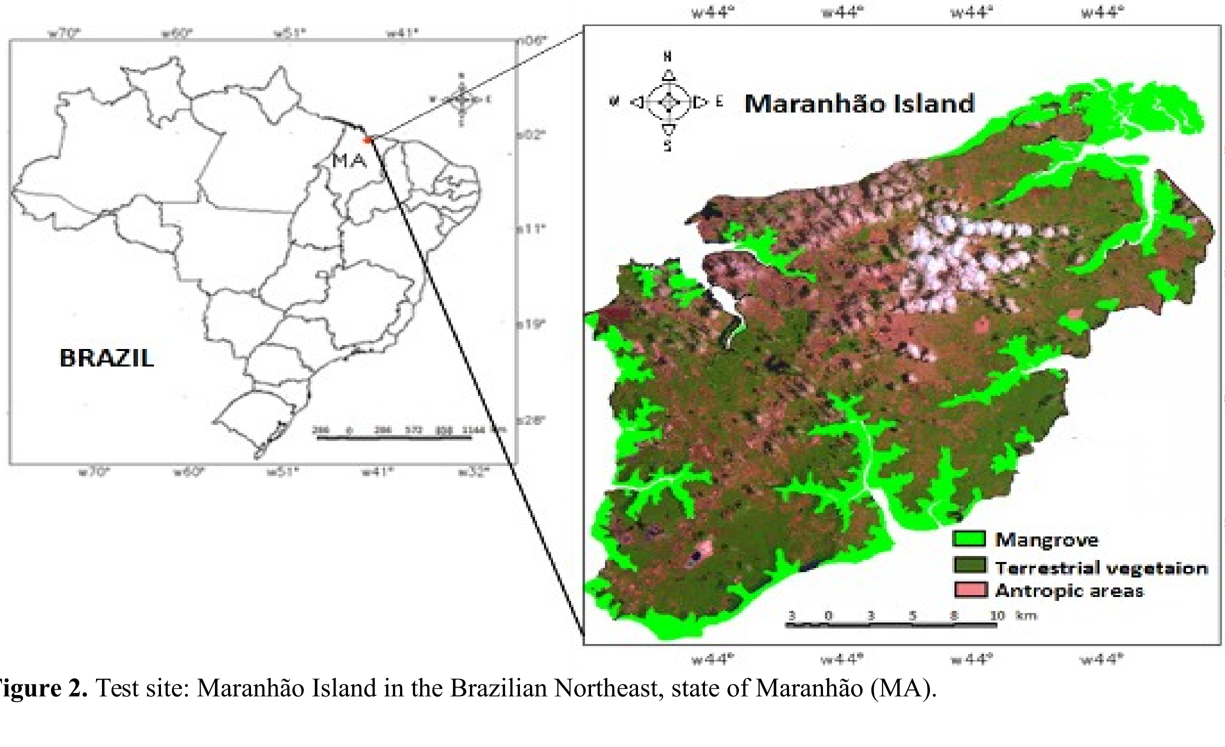

Figure 2. Test site: Maranhão Island in the Brazilian Northeast, state of Maranhão (MA).

mangrove, estuary, anthropic area, terrestrial vegetation and beach. In each cell, the majority land cover class defines the cell state.

As cell attributes, soil classes (Figure 3c), altimetry (Figure 3d) and tide height values were assigned to each cell at each inundation step. The most frequent soil type at each cell was identified from the official soil mapping by the Brazilian Agricultural Research Corporation (EMBRAPA 2002). The minimum value of altimetry was computed for each cell from the Shuttle Radar Topography Mission (SRTM) DEM (Miranda 2005). The tide height on Maranhão Island is 6 m on average (Ferreira 1988) and was validated by tide data from the oceanographic database of Brazilian Navy[2]

Model Behavior

In order to run a model experiment from the conceptual model, a set of rules, or logical constraints, guides the behavior of cell condition and transitions. The initial condition (cell state) defined by the mangrove cell, water cell, anthropic cell, terrestrial vegetation cell and beach cell changes according to the process of sea-level rise following specific rules:

A) The process of sea-level rise: we simulate a scenario of sea-level rise up to 1 m, distributed as an arithmetic progression of reason 0.1 m (“***i***") over 10 intermediate elevation steps (the scenarios of sea-level rise), as demonstrated in the equation (1):

(1) *Sea-Level Rise* = *wc* + *(*elevation step *X 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 0.1m/elevation step.

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) *Flux* = Sea-level rise / neighboring cells,

Where:

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

“Neighboring cells” corresponds to the number of neighboring cells of each water cell. The water cells may have up to 8 neighboring cells.

B) Land cover dynamics: the land cover changes and the persistence or migration of mangrove areas follow specific rules:

a) Mangrove only exists in the area under tidal influence (ATI), as indicated by Field (1995) and Spalding *et al.* (2010);
b) The ATI is determined by the tide height (Miranda *et al.* 2005);
c) Initially, the ATI value is 6 m, as indicated by Ferreira (1988) and validated by tide data from the oceanographic database of the Brazilian Navy. As the sea-level rises, the value of ATI is updated by adding the sea level increment;
d) At every elevation step of sea-level rise, mangrove cells may migrate to adjacent cells since natural or anthropogenic barriers are not present on ATI. In this case, cells of land cover class assigned as terrestrial vegetation are converted to mangrove cell (mangrove migration);
e) Cells of land cover class assigned as anthropic cells are anthropic barriers. 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, or when the cell land cover is equal to beach;
f) 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 cell (mangrove inundation);
g) Cells classified as anthropic cell, beach cell, and terrestrial vegetation cell can also be inundated by the rising of the 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.

Results and Discussion

The model simulated scenarios of sea-level rise on Maranhão Island for ten elevation steps from 0.1 to1 m. For every scenario we computed the resulting variation of the mangrove area, mangrove inundation, and mangrove migration. The total mangrove area on Maranhão Island in 2011 was 17,387 ha, corresponding to the initial condition. Figure 4 presents the total mangrove area simulated at each sea level scenario. From the initial condition up to 0.3 m of sea-level rise, the mangrove area presented an increase of approximately 1,173 ha which corresponds to a percentage rate of 6.75 %.

[2] www.mar.mil.br/dhn/chm/tabuas

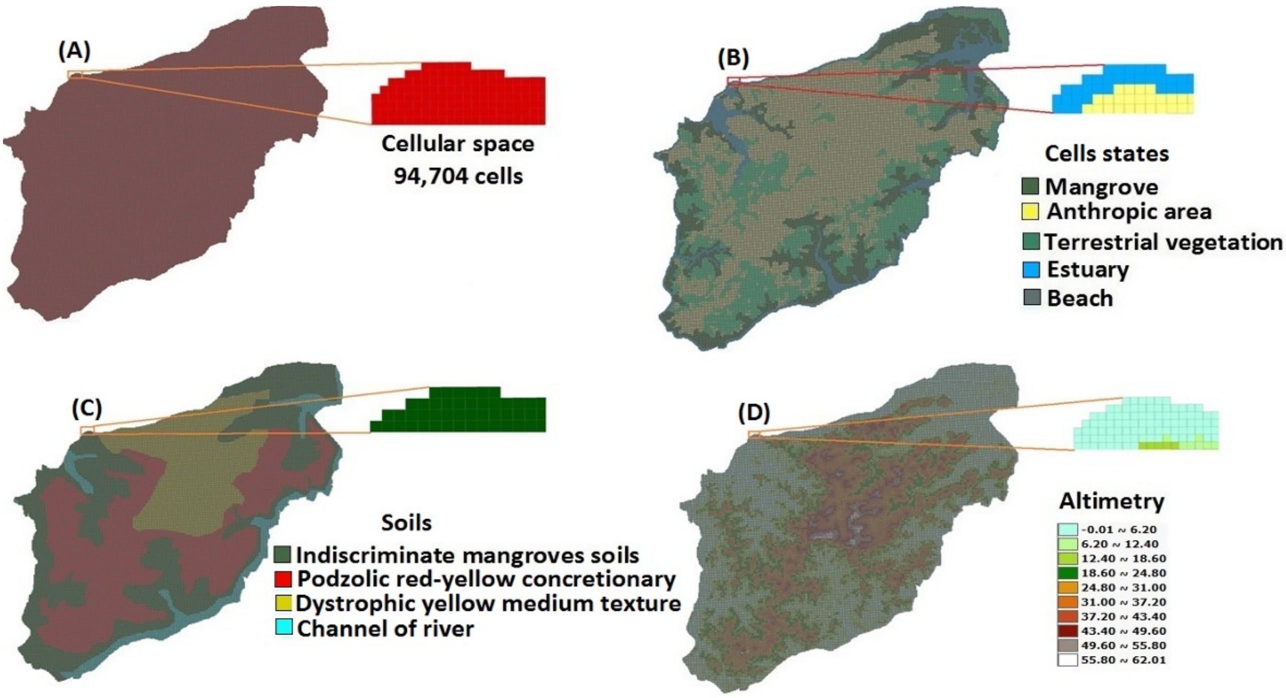

Figure 3. Cellular space: (A) Empty cellular space (B); Cell states; (C) Attribute-soils; (D) Attribute-Altimetry.

These results are consistent with the literature that indicates positive variation of mangrove areas according to sea rise levels, also depicting potential areas of mangrove increase as the salt water increasingly penetrates in rivers and estuaries (Lacerda et al. 2007). França et al. (2012) investigating the impacts of sea-level rise and climate change on the Brazilian Amazon coast during the late Holocene confirmed that the sea-level rise is the most likely factor that may cause the expansion of mangroves.

After simulation step 3, sea-level rise higher than 0.4 m resulted in the retraction of mangrove areas. This pattern of mangrove reduction continued until the value of 0.8 m of sea-level rise, moment in which the mangrove area showed a slight increase and, at the final elevation step, the simulated area was 17, 028 ha; 2.06 % less than the initial mangrove area.

Comparing the highest value of mangrove area (18,560 ha at elevation step 3) in relation to the lowest value simulated (17,028 ha at elevation 10), the most significant rate of mangrove retraction was 8.25% (1,532 ha).

The simulation of mangrove migration and inundation in each elevation step is shown in Figure 5. The process of mangrove migration increased about 1,327 ha at the first step 1 (0.1 m of sea level elevation), but in the subsequent events it decreased, ranging from 222 to 6 ha, when the sea-level rise reached the maximum value (1 m).

The loss of mangrove area remained approximately constant, in average 119 ha, up to 0.3 m of sea-level rise, and presented a continuous increase during the simulation of sea level over 0.4 m, ranging from 679 to 957 ha.

The migration and colonization of new mangrove areas may be limited by human occupation of adjacent areas, which restricts this ecosystem's capacity to adapt to new conditions (Scavia et al. 2002). This may explain the loss of mangrove area for the simulation values of sea-level rise higher than 0.3 m (see Figure 4).

Ellison (1993) stressed the importance of elevation relative to tidal spectrum as an indicator of mangrove problems, such as erosion and inundation. Inundation, defined by the DEM variable, is probably the main factor causing mangrove dieback in Maranhão Island simulation. In addition, the resulting mangrove increment is just potential, since the pattern of peat accretion has to be higher than the rate of sea-level rise for mangrove effective colonization. Studies have also demonstrated that during the Holocene, the post-glacial sea-level rise and changes in river water discharge have been considered the main driving forces behind the expansion/contraction of mangroves in northern Brazil (Cohen et al. 2008, Lara & Cohen 2009, Guimarães et al. 2010, Smith et al. 2012). In order to enhance our modeling approach, both sediment and water discharge dynamics should be present in further versions of the conceptual model.

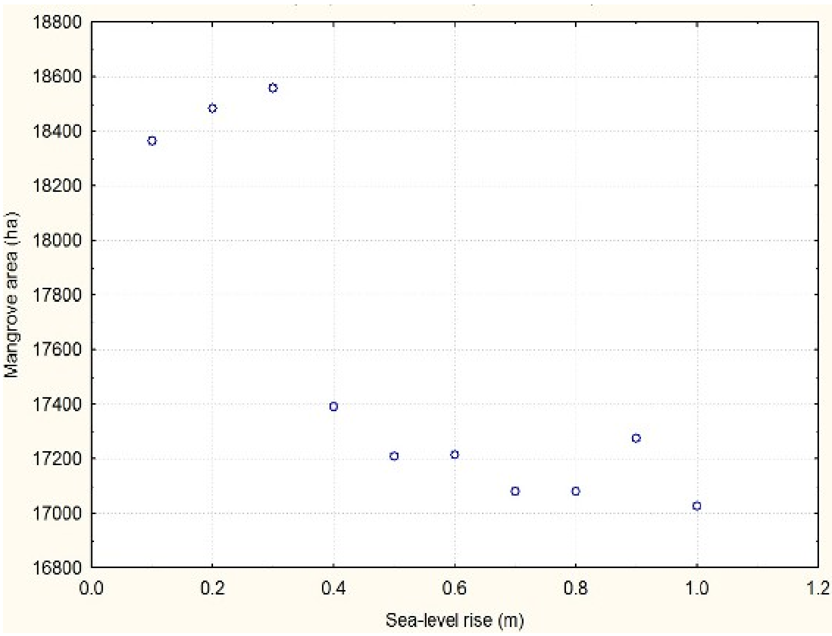

Figure 4. Total mangrove area (ha) according to sea-level rise (m) simulated for Maranhão Island, Brazil, simulated by the proposed model.

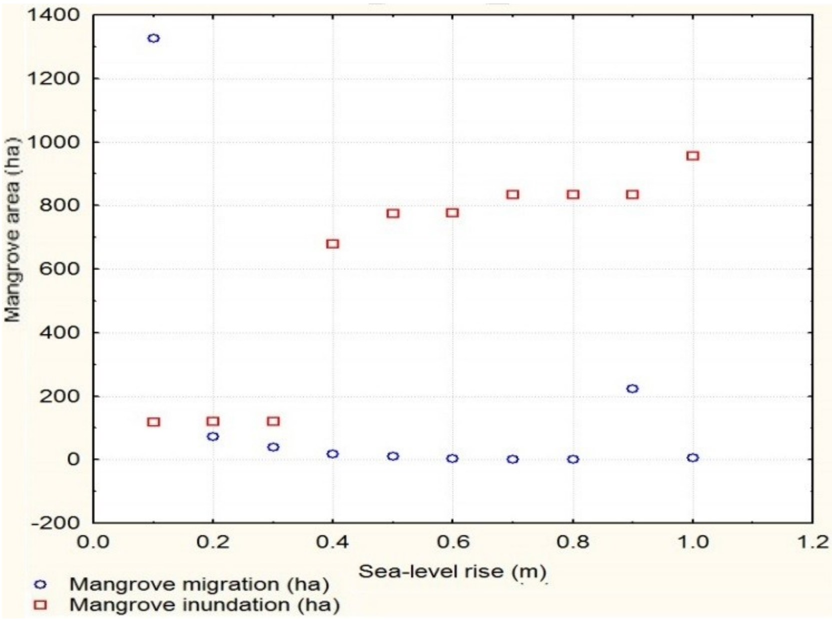

Figure 5. Mangrove migration and inundation (ha) according to sea-level rise (m) simulated for Maranhão Island (Brazil) by the proposed model.

On Maranhão Island, the anthropic area corresponds to 48.77% of the present land use classes, estimated as approximately 43874, 81 ha, and is spread out along the island. Even without any projection of urban expansion in our modeling, impervious surfaces in areas of indiscriminate mangrove soils can prevent mangrove progress. This barrier effect can be specially observed in the north part of Maranhão Island: Sao Luis downtown is located in mangrove soils. In urban centers, modeling simulations can be helpful for the previous identification of mangrove areas sensibility to the impacts of sea-level rise merged with the influence of anthropic areas and natural barriers that can minimize the adaptive capacity of the mangrove to sea-level rise (Cahoon et al. 2006). The migration and colonization process of new mangrove areas

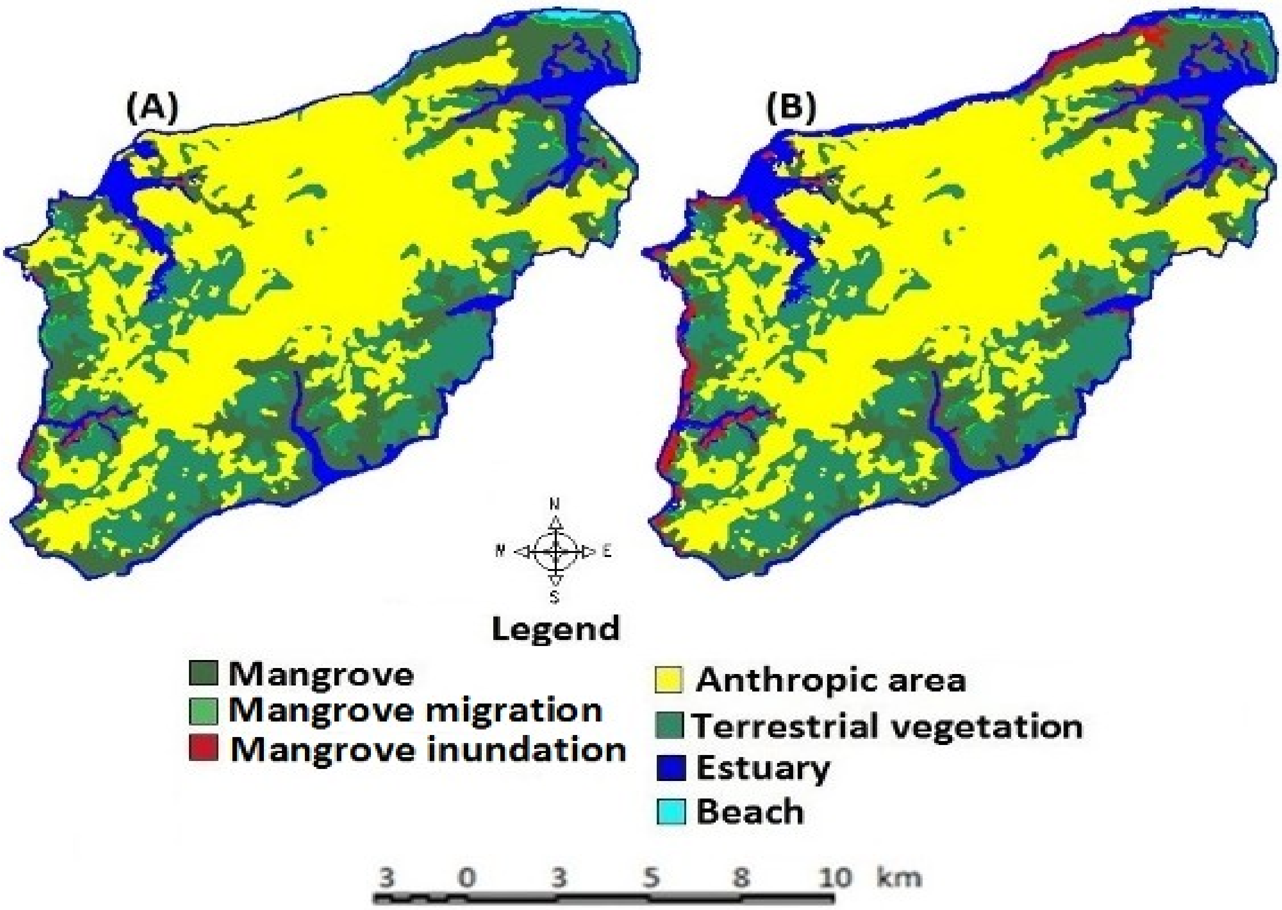

Figure 6. Land cover classes and spatial distribution of the mangrove areas on Maranhão Island: a) Situation at the start of the simulation (0.1 m of sea level); b) final land cover distribution after simulating 1 m of sea-level rise.

may be limited by human occupation and by natural barriers in adjacent areas (Scavia *et al*. 2002, Soares, 2009, Faroco *et al*. 2010). Figure 6 shows the spatial distribution of the mangrove at the start of the simulation (Figure 6a) and after the simulation (Figure 6b), with respectively 0.1 and 1 m of sea-level rise.

As expected, mangrove migrated to areas under slight influence of human activities, such as the northeast and west parts of Maranhão Island (Figure 6a), however, the topography in these areas is low, thus the expansion of new mangrove areas is superimposed by the inundation process resulting from the sea-level rise scenarios used in the present study (Figure 6b).

As supported by Berger *et al*. (2008), the use of spatially explicit modeling can help understand the response pattern of the mangrove to climate change and to other environmental tensors. Therefore, our results are a first attempt to understand mangrove patterns of a specific study case (Maranhão Island), associated to the simplification of this complex process proposed in our conceptual model.

Conclusion

Using the model to simulate sea level scenarios on Maranhão Island, one could identify the mangrove responses at a specific study site. The mangrove area expanded when favored by the sea-level rise of up to 0.3 m; however, it retracted for values of sea-level rise from 0.4 to 1 m. This result demonstrates the complexity of the mangrove response pattern to sea-level rise, especially in areas with intense anthropic presence such as the Brazilian coastal zone.

To characterize and quantify the influence of sea-level rise on mangrove, it's necessary to analyze its impacts, not only concerning the response in area (increase or reduction), but also in the spatial distribution of mangrove and in its capacity to provide products and services to coastal zone. Different adjacent land cover can act as barriers to expansion of new mangrove areas, and therefore must be included in the analysis. Population demands on mangroves should also be included in further analysis.

Modeling and simulation exercises can provide useful information to support the proposition of mitigation measures in decision-making instruments for the coastal planning in relation to climate changes, such as the Coastal Zoning. In this context, spatial explicit models based on cellular automata can be used to an early identification of areas with different degrees of sensitivity, which would allow the formulation of strategies based on local specificities for the region under analysis.

The proposed model in the present study can be applied to other study sites that have similar input database. The model can also be improved, by adding new components to model the sea-level rise impacts. For further studies of Brazilian mangroves, the model can include additional components to encompass, for example, climate, as well as hydrological and sedimentation dynamics in order to improve the understanding of mangrove and sea-level rise relationships.

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