CILAMCE 2017
Florianópolis - Santa Catarina - Brazil

MODELING OF THE DYNAMICS MANGROVE FRONT TO SEA-LEVEL RISE ON THE BRAZILIAN COAST

Adriam Freitas Ribeiro

Luís Jorge Mesquita de Jesus

adrianfreitasr@yahoo.com.br

luisjorged25@hotmail.com

Laboratório de Modelagem e Simulação de Sistemas Energéticos, Universidade CEUMA

Rua Josué Montelo, 1, Renascença II, 65075-120, São Luís, Maranhão, Brasil

André Luís Silva dos Santos

andresantos@ifma.edu.br

Instituto Federal do Maranhão

Avenida Getúlio Vargas, 4, Monte Castelo, 65030-005, São Luís, Maranhão, Brasil

Denilson da Silva Bezerra

denilson_ca@yahoo.com.br

Laboratório de Geotecnologias, Universidade CEUMA

Rua Josué Montelo, 1, Renascença II, 65075-120, São Luís, Maranhão, Brasil

Abstract. *In the present study is propose a methodological approach to simulate the resistance pattern of the mangrove to sea-level rise, using spatially explicit modeling based on cellular automata; the proposed model is called the BR-MANGROVE. The simulation considers 88 events of elevation from 0.011 to 0.97 m according an arithmetic progression of reason 0.011 m for the time interval from 2012 to 2100. The case study area is the Maranhão Island – Brazil, which contains extensive mangrove area, and is densely occupied. The results presented demonstrated that mangrove had 13 resistance patterns, where the first was characterized by an elevation range from 0.01 to 0.13 m for the period 2013-2024. In this interval, the mangrove area remained approximately constant, with values of the order of 17,711 ha for the total area, and 16,916 ha of remaining area, which corresponds to 4.49% (795 ha) of expansion. After the first resistance pattern, mangrove showed 12 subsequent patterns of resistance and decline of area until the finish of the simulation. The results obtained through the BR-MANGROVE suggest that modeling experiments can be used to promote a better understanding of patterns of the mangrove responses to potential events of sea-level rise, especially in areas of complex use.*

Keywords: *Sea-level rise, Mangrove, Modelling, Cellular Automata, Coastal Zone.*

1. INTRODUCTION

The process of anthropogenic warming of the climate system initiated since the pre-industrial is unequivocal (IPCC 2007). One typical effect of this process is the phenomenon of sea level rise.

According to the fourth assessment report of the Intergovernmental Panel on Climate Change (AR4-IPCC), the estimated total rise in sea level during the twentieth century ranged between 0.12 m to 0.22 m by the last decade of XXI century (2090-2100), and projections indicate that sea level can oscillate from 0.26 m to 0.59 m. 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 the sea level rise, the mangrove ecosystem can suffers profound modifications, such as decreasing or increasing the area of the ecosystem, migration, loss of biological diversity, and changes in supplying environmental goods and services (McLeod & Salm 2006; Gilman *et al.*2008). However, studies in this regard are still lacking and inconclusive (Alongi 2008).

The 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 (Luo *et al.* 2010). For the goods and services offered by mangroves, it is estimate annual values ranging from US$ 200,000,000 to US$ 900,000,000 per km^2 (Well *et al.* 2006).

The distribution of mangroves in Brazilian territory spreads from Brazilian border with French Guiana, just above the line of Ecuador (04º 30' N), until 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, with length of approximately 8,900 km^2 (Kjerfv *et al.* 2002). Brazil has 13,000 km^2 of mangroves, being the second country in mangrove area (Spalding, Kainuma & Collins 2011).

Understand the dynamics of the impacts of climate change on mangroves in Brazil, especially the sea level rise, is a great challenge. Understanding how these impacts and other anthropic amendments may contribute to depreciation of the environmental quality in the mangrove and in its capacity to produce goods and services to coastal zone is fundamental for both the scientific knowledge and the population that depends on mangroves (Faroco, Andriguetto-Filho & Lana 2010).

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

Proceedings of the XXXVIII Iberian Latin-American Congress on Computational Methods in Engineering
P.O. Faria, R.H. Lopez, L.F.F. Miguel, W.J.S. Gomes, M. Noronha (Editores), ABMEC, Florianópolis, SC, Brazil, November 5-8, 2017.

As computational models can be used as an additional tool to understand and simulate impacts over natural environments, our work aims to contribute for further strategies for mitigation and adaptation of the effects of climate change on mangroves, especially for those adjacent to urban areas.

1.1 Conceptual Model

In the conceptual model proposed, we considerate that the sea level rise and the land cover in adjacent areas may cause various impacts to mangrove as indicated by specific literature (Alongi 2007; Scavia *et al.* 2002; Gilman *et al.* 2008), namely: augmentation of water column, displacement of the area over tidal influence, mangrove inundation and the process mangrove migration to continent. Figure 3 shows the general conceptual model that structures the proposed model. This general framework can support further extensions, as any of these components can became as complex as any theoretical subjacent assumptions or modeling structures would be created.

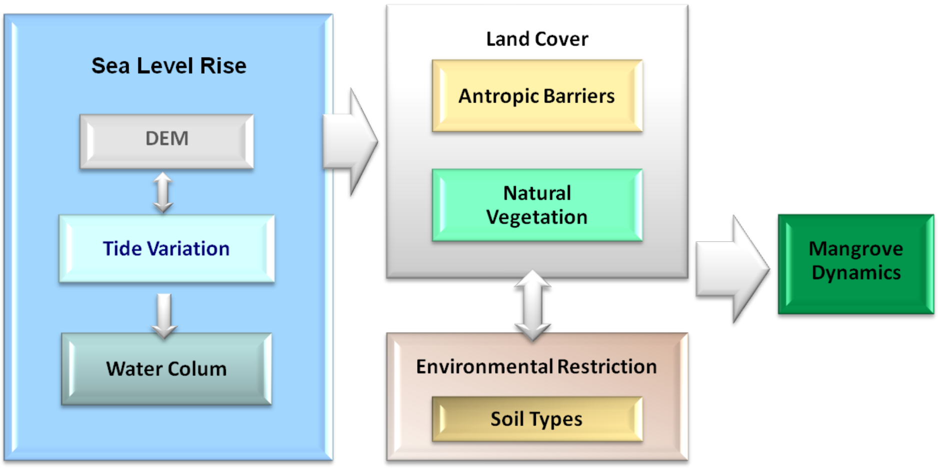

Figure 1 Diagram demonstrating the general conceptual model proposed to simulate the impacts of sea level rise over mangrove areas.

In the Sea Level Rise module, the value of the water column in relation the topography of adjacent areas (indicated by the Digital Elevation Model - DEM) is used as reference for the process of inundation of the mangrove areas; we consider that this is a negative impact, since the inundation may reduce the area of the mangrove and yet affect its ability to provide goods and services to the coastal zone, since it may lead to decrease in the area of the ecosystem.

The tide height defines the area over tidal influence (Miranda *et al.* 2002), region where the mangrove may colonize, with the sea level rise the over tidal influence is displaced, favoring the migration of mangroves as indicated by the literature (Ellison 1993; Schaeffer-Novelli Y.; Cintron-Molero & Soares 2002; Gilman *et al.* 2008). We consider that this phenomenon can be considerate a positive impact because promote the expansion of mangrove areas.

In the Land Cover module, each land cover type can be considered either 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, Andriguetto-Filho & Lana 2010). Here, anthropic barriers are represented by areas where the native vegetation was removed and converted to impervious surfaces as result of human activities. Natural barriers are indicated for regions that are out of reach of the area over tidal influence, beaches and locals that have unsuitable soil for colonization of mangrove.

In the environmental restrictions module, only soil type is considered for our modeling approach. Mangroves grow on substrates with high content of silt and clay, with strong tidal influence, the presence of high levels of salts and generally in conditions very close to anoxia (McLeod & Salm 2006; Spalding, Kainuma & Collins 2011). In general, specific soil type, as indiscriminate mangroves soils, holds ideal conditions for colonization by mangrove typical vegetation, and other soils (dystrophic yellow medium texture and podzolic red-yellow concretionary) are considered as barriers to occupation of the mangrove.

For an specific area, the interaction from sea level rise over the terrain, the land cover pattern and environmental constrains will determine the conditions for mangrove persistence, migration or retraction, leading to different impacts over its goods and services provisions, which are considered at the Mangrove dynamic module.

2. METHODOLOGY

2.1 The Modeling Environment

The modeling process was implemented using Simulation and Modeling of Terrestrial System-terraME (see http://www.terrame.org/doku.php), a toolbox for spatially explicit modeling integrated with geospatial databases. It provides a programming environment for spatial dynamical modeling, supporting cellular automata, agent-based models, and network models running in 2 D cellular spaces (Carneiro *et al.* 2013). We used Lua, an open-source interpreted language with extensible semantics to implement the model source code at TerraME.

The model of the present study is based in the cellular automata computational model. A cellular automata is idealized as a logical system, which has as the basic unit the concept of cell. Each cell has a neighborhood of cells and a discrete state that may vary during the simulation according to its transition rules (Wolfram 1983).

2.2 Test Site

São Luís Island, also known as Maranhão Island (Figure 2) is an archipelago with more than 50 islands of various sizes and origins, located on the northern coast of Maranhão estate, 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%, occupying 146,49 km^2 (Rebelo-Mochel 2003b). Another striking feature of the Maranhão Island is the presence of macromareal that can vary from 6 to 7 m (Ferreira 1988).

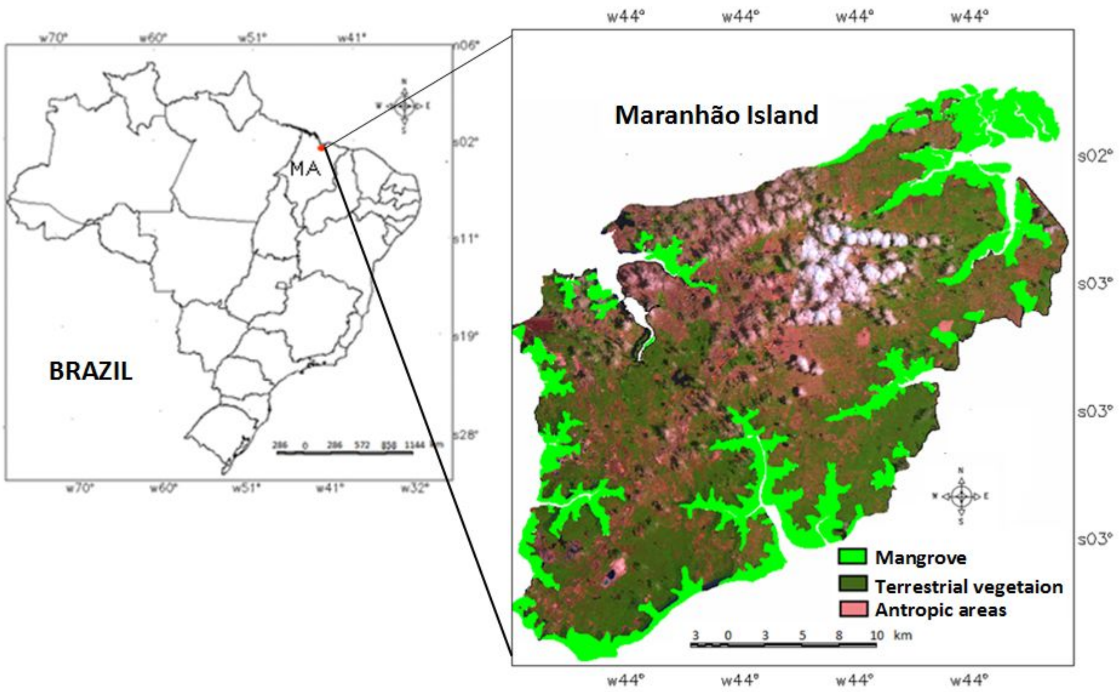

Figure 2 Study area: Maranhão Island in the Brazilian Amazon, state of the Maranhão (MA)

The topography at Maranhão Island is gently undulating, with altitudes up to 60 meters (Pereira & Zane 2007). It favors severe saltwater intrusion in rivers and form 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 by three main soil classes (Figure 3): indiscriminate mangrove soils, yellow dystrophic medium texture soil, and red-yellow concretionary podzolic (UEMA 2000; EMBRAPA 2002).

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

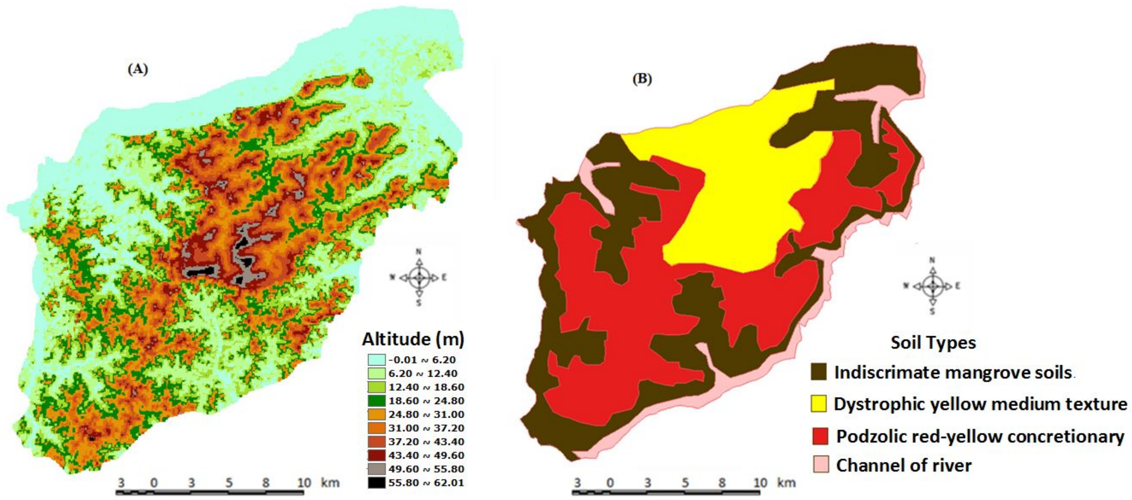

Figure 3 Altimetric and pedological characteristics of the Island Maranhao. (A) - Digital Elevation Model (DEM) for Maranhão Island obtained from SRTM data. Source: Brazil in relief/EMBRAPA (Miranda 2005). (B) – Pedological map. Source: EMBRAPA (2002).

2.3 Geographical Database and Cell States

For the simulation procedure, a geographical database was organized in a cellular space using TerraView 4.2.0 geographical information system (INPE, 2011). A cellular space containing 94,704 cells divided the study site in regular partitions of 1 ha of area (100 x 100 m). Each cell has a unique state and a set of attributes that defines this state at a certain time. During the simulation procedures, the states and attributes of every cell can change according to the transition rules.

The land cover classes that characterized the initial state of the cells are: mangroves, estuarine water, anthropic areas, terrestrial vegetation and beach. These classes correspond to a land cover mapping for 2011, produced from visual interpretation of ETM/Landsat5 images and on previous official mangrove mapping from the Brazilian Institute of Environment and Natural Resources (IBAMA) for 2008.

Soil classes, altimetry and tide height values constituted the attributes of each cell. 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 the altitude data was computed for the cellular space from the digital elevation model (DEM) based on Shuttle Radar Topography Mission (SRTM) images (Miranda 2005). The tide height in the study area is on average 6 m, as indicated by Ferreira (1988) and validated by tide data from the oceanographic database of Brazilian Navy (see site: http://www.mar.mil.br/dhn/chm/tabuas/).

2.4 Model Behavior

In order to run a model experiment from the conceptual model, a set of rules, or logical constraints, guides the behavior of the cell condition and transitions. The initial condition, defined by the mangrove and other land cover classes (cell estates) changes according to the process of sea level rise based on the following rules.

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

(1) *Sea Level* = *wc* + *(*inundation step ** i)*

Where*: **"Sea Level"*** is value of the sea level rise at ***"inundation step";***

"Inundation step" corresponds the dynamic of elevation of the water column. We consider that each inundation step is equivalent the one year;

"wc" is the value of water column (in meters) at current step in each cell classified as estuarine water*;*

"i" is a constant related to the sea level rise increment, given by the amount of sea level rise (which is 1 m) divided by the number of steps until the end of the simulation, therefore ***"i"*** value is 0.1m/inundation step.

The flux of water between cells is directed of the cells classified as sea (estuarine water) towards neighboring cells that have the altitude less than the sea level rise, as presented in equation (2):

(2) Flux = Sea Level / neighboring cells, were:

"Flux" is the inundation which occurs between cells;

"Sea Level" is value of the sea level rise at ***"step";***

"Neighboring cells", cells not classified as estuarine water.

B) Areas over Tidal Influence (ATI)

- Areas over tidal influence (ATI) are determined by the tide height that is given by the difference between the maximum tidal value (high tide) and the minimum tidal value (low tide) according to Miranda *et al.* (2002);
- Initially, the ATI value is 6 m, as indicated by Ferreira (1988) and validated by tide data from the oceanographic database of Brazilian Navy. As the sea level rises, the value of ATI is updated by adding of the sea level increment.

C) Land cover dynamic: to define the land cover changes and the persistence or migration of mangrove areas the following rules are proposed:

a. Mangrove only exists in areas submitted to tidal influence, as indicated by Field (1995) and Spalding, Kainuma & Collins (2011);

b. At every inundation step of sea level rise, mangrove area may migrate to adjacent cells since natural or anthropogenic barriers are not presents on areas over tidal influence. In this case, cells classified as terrestrial vegetation will be considered mangrove, this process provides an increasing in the mangrove area;

c. Anthropogenic barriers correspond to the cells classified as anthropic areas. Natural barriers correspond to cells which the altimetry attribute is higher than the ATI, or the soil attribute is different than the indiscriminate mangrove soil, or the cell land cover is equal to beach;

d. The inundation of mangroves occurs when the height of the water column is greater than or equal to the altimetry of adjacent cells classified as mangrove. In this case, cells classified as mangrove will be considered estuarine water, this process provides an decrease in the mangrove area;

e. Cells containing other land cover classes: anthropic areas, beaches, and terrestrial vegetation, can also be suppressed by the rising of the sea level. When the height of the water column is greater than (or equal to) the altitude of adjacent cells of the specific class cells, the cell will be then considered estuarine water.

3. RESULTS AND DISCUSSION

The model code was implemented in language Lua and it will be available on the site of the terraME (simulation platform free) shortly after the publication of the paper.

For the test site, the model simulated the sea level rise within 10 time steps, with additional values according to arithmetic progression from 0.1 to1 m. At each time step we computed the variation of the total mangrove area, the inundated mangrove area (loss area) and the migration of mangrove area (gain area).

From the initial total mangrove area at Maranhão Island was 17,387 ha (Figure 4), the results of the simulation evidenced that mangrove responded to sea level rise of up to 0.3 m with increment of area of the order of approximately 977 to 11,173 ha (5.62 to 6.37 %, respectively). The largest rate of increase was observed to sea level rise of 0.3 m, where the mangrove reached a total area of 18,560 ha.

These simulation results were consistent with the scientific literature, indicating mangrove areas positive variation according to sea rise levels, also depicting potential areas of mangrove increase as the salt water increasingly penetrates in rivers and estuaries (Lacerda, Menezes & Molisani 2007; Alongi 2008). França *et al.* (2012) investigating the impacts of sea level rise and climate change on the Brazilian Amazon coastal during the late Holocene confirmed that the sea level rise is the most likely factor that may cause the expansion of mangroves.

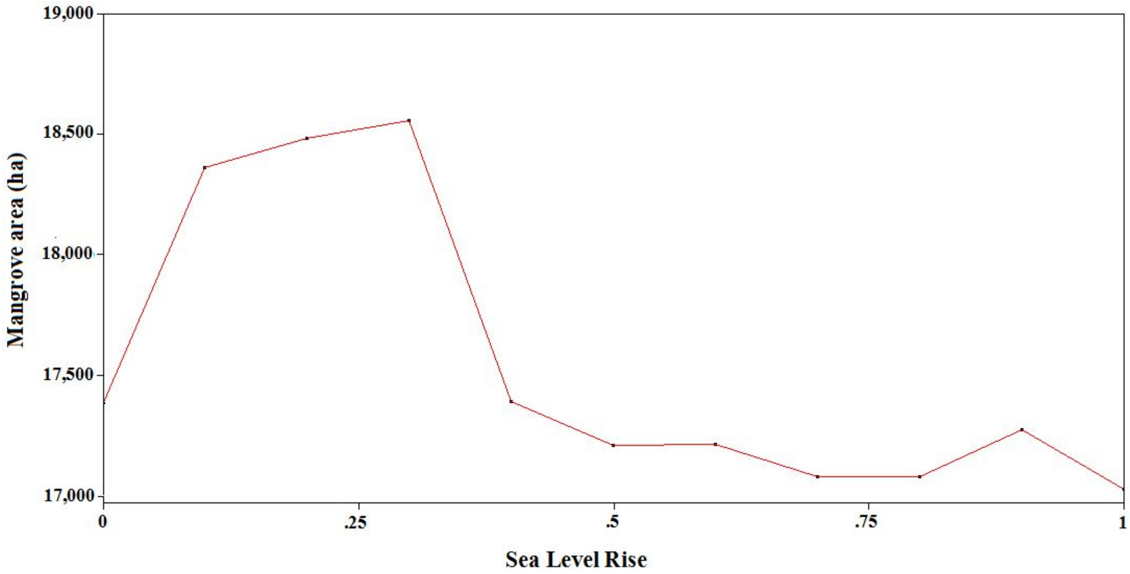

Figure 4 Total mangrove area (ha) according to sea level rise (m) simulated for Maranhão Island, Brazil, by the proposed model.

The results presents in the Figure 4 also demonstrated loss of mangrove areas to rising sea values above 0.4 m, this fact may indicates the complexity of the response pattern of the mangrove ecosystem to sea level rise, once the mangrove areas also can be lost (Ellison, 1993). The rate of loss mangrove area was of 8.25%, talking in consideration the biggest simulated mangrove area (18.560 ha) in relation to lowest value of mangrove area predicted by the model (17.028 ha).

Of all the climate change outcomes, relative sea level rise may be the greatest threat to mangrove; this ecosystem has been used as a tool for assessing of the sea level rise (Walters *et al.* 2008). However, the mangrove responses to sea level rise depends on factors such as topography, tidal range, land cover in adjacent areas, coastal dynamics and the mean rate of sea level rise (Mcleod & Salm 2006; Lovelock & Ellison 2007).

Through the proposed model, we simulated processes of migration and loss of the mangrove area (Figure 5). The process of mangrove migration showed an increase of about 1,327 ha in the inundation step 1 (0.1 m of elevation), in the events subsequent of elevation, the migration of mangrove areas was decreasing, its values ranged from 222 to 6 ha, the extent that the sea level rise reaches the maximum value (1 m).

The simulate data demonstrated that the process mangrove area loss remained approximately constant (in average 119 ha) up to 0.3 m of sea level rise, however, for amounts over 0.4 m, the loss of mangrove areas had a continuous increase during the simulation of sea level rise with values that ranging from 679 to 957 ha.

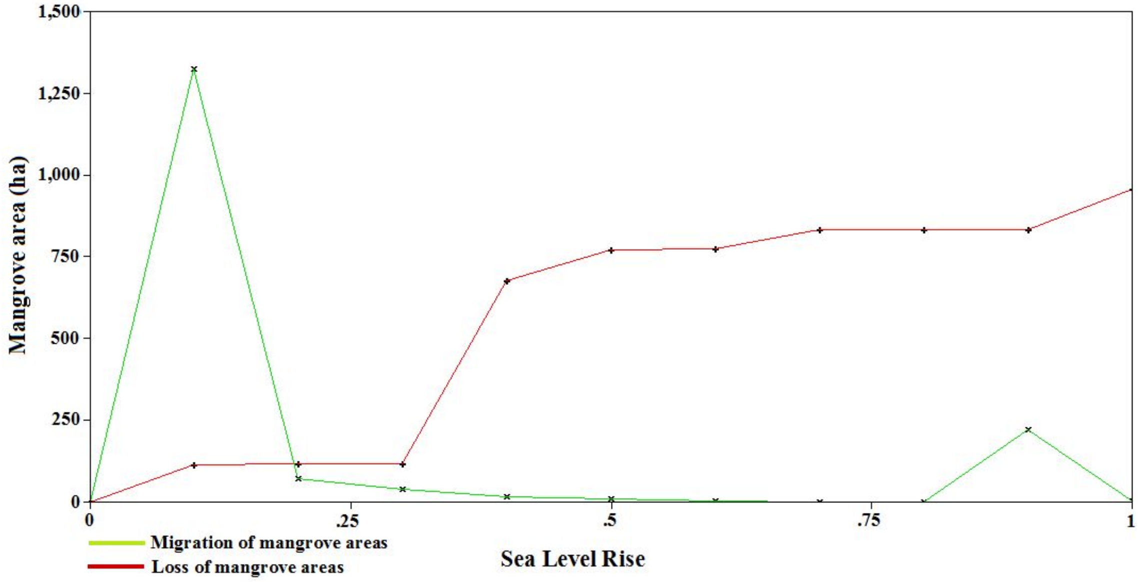

Figure 5 Mangrove migration and loss (ha) according to sea level rise (m) simulated for Maranhão Island (Brazil) by the proposed model.

The data simulate demonstrated that for values of elevation above 0.2 m, there was reduction of the process of migration of the mangrove area, this fact may indicate the influence of the forms of human occupation and others natural barriers.

The process migration and colonization of new mangrove areas may be limited by human occupation and for natural barriers in adjacent areas (Scavia *et al.* 2002; Soares, 2009; Faroco, Andriguetto-Filho & Lana, 2010). Figure 6 shows the original spatial distribution of the mangrove (Figure 6a) and after the simulation (Figure 6b), with respectively 0 and 1 m of sea level rise.

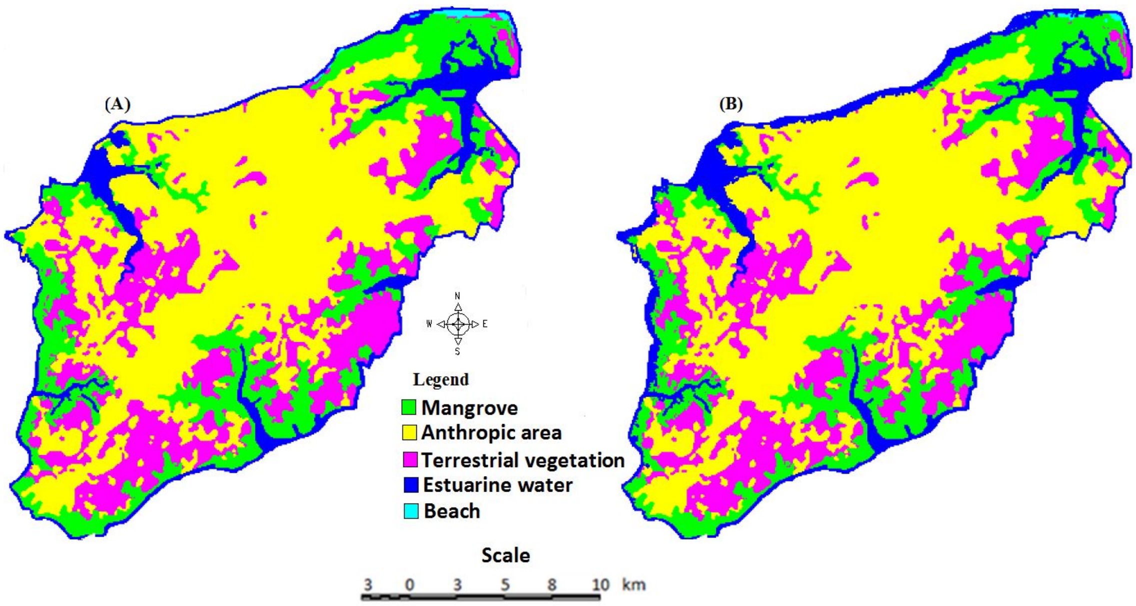

Figure 6 Land cover classes and the spatial distribution of the mangrove areas at Maranhão Island: a) original 2011 mapping before of the simulation (0 m of sea level); b) final land cover distribution after simulating 1 m of sea level rise.

As expected, mangrove migrated to areas under little influence of human activities, as observed for the northeast and west parts of Maranhão Island (Figure 6). In the southeast part of the island, the topography and the presence anthropic areas, limited the mangrove migration.

In the 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 (Cahoon *et al.* 2006). The use of computational models can help understand the response pattern of the mangroves to climate change (Doyle, 2003).

4. FINAL REMARKS

In the conceptual model propose, we consider the elements: sea level rise, areas over tidal influence, the mangrove, presence of barriers anthropic and natural, types of soils and topography. In subsequent studies, the model may be increased by elements that can describe alterations in the hydro period in estuarine environment, in the response pattern per mangrove's species to sea level rise, among others.

The implementation of the model was made in a simulation platform free and with open code; this may facilitate the occurrence of criticism and suggestions about the research present.

The proposed model showed simulation results consistent with the literature focused on the impacts of the level rise on mangroves. From the simulation results, we observed that the mangrove is favored by sea level rise of up to 0.3 m, once the mangrove had increasing in its area, with positive effects for goods and services provided by the mangrove ecosystem; however, the mangrove response to values from 0.4 to 1m of elevation showed inverse pattern. This fact demonstrates the complexity of the response pattern of mangrove ecosystem to sea level rise.

To characterize and quantify the importance of mangrove for climate change is necessary to analyze the impacts, not only concerning the response in area (increase or reduction), but also in the spatial distribution of mangrove and its capacity to provide goods and services to coastal zone. Different adjacent land cover can act as barriers to expansion of the mangroves, and therefore must be included in the analysis, especially those from human activity. Population demands over mangroves should also be considered for further analysis.

Modeling and simulation exercises can provide useful information to support the proposition of mitigation measures in decision-making instruments for the coastal zone, such as the coastal zoning, and the ecological-economic zoning. In this context, spatial explicit models based on cellular automata can be used to identify in advance areas with different degrees of sensibility, which would allow the formulation of strategies based on local specificities of the region under analysis.

ACKNOWLEDGEMENTS

The authors of this work are grateful to Laboratory of Modeling and Simulation of Energy Systems and Laboratory of Geotechnologies, both of the CEUMA University, for the support granted to this research.

REFERENCES

Alcantara-Filho, P (1982). *Diversificação intraespecífica do caranguejo-uçá Ucides cordatus (Linnaeus, 1763) (Crustacea - Decapoda - Brachyura) entre os manguezais dos rios Pará, no estado do Pará, e Pomonga no estado de Sergipe (Brasil): 00o41›S-10o40›S.* 1982. 192 p. Tese (Doutorado) – Instituto Oceanográfico da Universidade de São Paulo, São Paulo.

Alongi, D.M (2007). Resilience of mangrove forests, tsunamis, and global climate change. *Estuarine, Coastal and Shelf Science*, volume 76, issue: 1, Publisher Elsevier, 1-13. doi:10.1016/j.ecss.2007.08.024.

Alves, R.R.N. & Nishida, A.K (2004). Population structure of the mangrove crab *Ucides cordatus* (Crustacea: Decapoda: Brachyura) in the estuary of the Mamanguape river, Norhteast Brazil. *Tropical Oceanography*, v. 32, n. 1, 23-37.

Blankensteyn, A.; Cunha Filho, D.; Freire, A.S. (1997). Distribuição, estoques pesqueiros e conteúdo proteico do caranguejo-do-mangue *Ucides cordatus* (Linnaeus, 1763) (Brachyura: Ocypodidae) nos manguezais da Baía das Laranjeiras e adjacências, Paraná, Brasil. *Arquivos de Biologia e Tecnologia*, v. 40, n. 2, 331-349.

Botelho, E.R.O.; Santos, M.C.F.; Pontes, A.C.P. (2000). Algumas considerações sobre o uso da redinha na captura do caranguejo-uçá U*cides cordatus* (Linnaeus, 1763) no litoral sul de Pernambuco – Brasil. *Boletim Técnico-Científicodo Cepene*, v. 8, n. 1, 55-7.

Bouillion, S. *et al.*(2009). *Mangroves. The management of natural coastal carbon sinks*. D.d. A. Laffoley and G. Grimsditch. Gland Switzerland, IUCN: 13–20.

Branco, J.O. (1993). Bioecological aspects of *Ucides cordatus* (Linnaeus, 1763) (Crustacea, Decapoda) from Itacorubi Mangrove, Santa Catarina, Brazil. *Arquivos de Biologia e Tecnologia*, v. 36, p. 133-148.

Cahoon, D.R. *et al.* (2006) Coastal wetland vulnerability to relative sea-level rise: wetland elevation trends and process controls. In: Vhoevebn J.T.A. *et al*. (Eds.), *Wetlands and Natural Resource Management. Ecological Studies*, vol. 190. Springer-Verlag, Berlin/Heidelberg, pp. 271–292.

Carneiro, C.G.S. *et al.* (2013). TerraME: an extensible toolbox for modeling nature-society interactions. *Environmental Modelling & Software*.

Carqueija, C.R.G. (Coord.). (2008a). *Projeto caranguejo-uçá*: biologia e sustentabilidade – Manguezal de Saubara, Bahia. Relatório Técnico-Científico Final. 45 pp, Salvador: Faculdade de Tecnologia e Ciências.

Carqueija, C.R.G. (Coord.). (2008b) *Bioecologia do Cardisoma guanhumi (Latreille, (Crustacea, Decapoda, Gecarcinidae) no Rio Passa-Vaca, Salvador, Bahia*. Relatório Técnico-Científi co Final. Salvador: Faculdade de Tecnologia e Ciências.

Castro, A.C.L. (1986) Aspectos Bioecológicos do caranguejo-uçá *Ucides cordatus cordatus* (Linnaeus, 1763), no estuário do Rio dos Cachorros e no Estreito do Coqueiro,São Luís - MA. *Boletim do Laboratório de Hidrobiologia*, v. 7, 7-26.

Doyle, T.W. (2003). Books, M.A. Chapter 12: modeling mangrove forest migration along the southwest coast of Florida under climate change. *In:* Ning, Z.H., Turner, R.E., Doyle, T.W., Abdollahi, K. (Eds.), Integrated Assessment of the Climate Change Impacts on the Gulf Coast Region. GRCCC and LSU Graphic Services, Baton Rouge, LA, p. 211–221. 2003.

Ellison, J.C. (2003). Mangrove Retreat with rising sea-level, Bermuda. *Estuarine Coastal and Shelf Science,* 37(1), 75-87.

EMBRAPA MONITORAMENTO POR SATÉLITE (Campinas, SP). (2002). *Zoneamento ecológico-econômico do Estado do Maranhão: Pedologia*. Campinas. CD-ROM. Escala 1:500.000; Formato: Arquivo de Impressão (PRT); Projeções: UTM. (ZEEMA/02/053, Pedologia).

Faraco, L.F.D.; Andriguetto-Filho, J.M. & Lana, P.C.A. (2010). Methodology for Assessing the vulnerability of mangroves and fisherfolk to climate change. *Pan-American Journal of Aquatic Sciences*, 5(2): 205-223

Ferreira, H.O. (1998). Contribuição ao estudo das correntes de maré dos estreitos dos coqueiros e mosquitos, Maranhão. *Boletim LaboHidro* 8: 45-59, UFMA, São Luis.

Field, C. (1995). Impacts of expected climate change on mangroves. *Hydrobiologia* 295, 75–81.

França, M.C. (2012). The last mangroves Marajó Island-Eastern Amazon: Impact of climate change and/or relative sea-level changes.

Gilman, E.L. *et al.* (2008). Threats to mangroves from climate change and adaptation options, *Aquat. Bot*., doi:10.1016/j.aquabot.2007.12.009.

IBAMA (2011). *Proposta de Plano Nacional de Gestão para o Uso Sustentável do Caranguejo-Úça do Guaiaum e do Siri-Azul*/José Dias Neto, organizador. – Brasília, 156 p.

IPCC. (2007): *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds. Cambridge University Press, Cambridge, UK. 976 p.

Ivo, C.T.C. & Gesteira, T.C.V. (1999). Sinopse das observações sobre a biologia e a pesca do caranguejo-uçá *Ucides cordatus cordatus* (Linnaeus, 1763), capturado em estuários de sua área de ocorrência no Brasil. *Boletim Técnico-Científi co do Cepene*, v. 7, n. 1, 9-52.

Ivo, C.T.C. *et al*. (2000). Caracterização das populações de caranguejouçá *Ucides cordatus* (Linnaeus, 1763) capturadas em estuários do Nordeste do Brasil. *Boletim Técnico-Científi co do Cepene*, v. 8, n. 1, 9-43.

Ivo, C.T.C.; Dias, A. F. & Mota, R. I. (1999). Estudo sobre a biologia do caranguejouçá *Ucides cordatus cordatus* (Linnaeus, 1763), capturado no Delta do Parnaíba, estado do Piauí. *Boletim Técnico-Científico do Cepene*, v. 7, n. 1, p. 53-84.

Jankovski, M.; Pires, J.S.R. & Nordi, N. (2006) Contribuição ao manejo participativo do caranguejo-uçá *Ucides cordatus* (Linnaeus, 1763), em Cananéia – SP. *Boletim do Instituto de Pesca*, v. 32, n. 2, 221-228.

Kjerfve, B. (2002). Morphodynamics of muddy environments along the Atlantic coasts of North and South America. In: *Muddy Coasts Of The World: Processes, Deposits and Functions*. 1s ed., Amsterdam, Elsevier Science. pp. 479–532.

Lara, R.J. & Cohen, M. C. L. (2003). Sensoriamento Remoto. In: Os Manguezais da Costa Norte Brasileira/org. Marcus E. B. Fernandes 1a ed. Maranhão: Fundação Rio Bacanga, pp.13-30.

Luo *et al.* (2010). Modeling productivity in mangrove forests as impacted by effective soil water availability and its sensitivity to climate change using biome-BGG. *Ecosystem* 13: 949-965.

Lovelock, C.E. & Ellison, J.C. (2007). Vulnerability of mangroves and tidal wetlands of the Great Barrier Reef to climate change. *In:* Johnson, J.E., Marshall, P.A. (Eds.), Climate Change and the Great Barrier Reef: A Vulnerability Assessment. Great Barrier Reef Marine Park Authority and Australian Greenhouse Office, Australia, pp. 237–269.

Lowe, J.A. *et al.* (2009). *UK Climate Projections Science Report: Marine and Coastal Projections* (Met Office Hadley Centre, Exeter, UK), 12 pp.

McLeod, E. & Salm, R., V. (2006). *Managing Mangroves for Resilience to Climate Change.* IUNC, Gland, Switzerland. 64 pp.

Miranda, E. E. de; (Coord.). *Brasil em Relevo*. Campinas: Embrapa Monitoramento por Satélite, 2005. Disponível em: <http://www.relevobr.cnpm.embrapa.br>. Acesso em: 5 abr. 2013.

Miranda, L.B.; Castro, B. M. & Kjerfve. (2002) *Princípios de Oceanografia Física de Estuários.* – São Paulo: Editora da Universidade de São Paulo, 411 p.

Murray, B.C. *et al.* (2010). A Payments for blue carbon: potential for protecting threatened Coastal Habitats. Nicolas Institute Policy Brief. 8 p. Available in: <http://nicholasinstitute.duke.edu/oceans/marinees/blue-carbon>. Accessed at 12/11/12.

Nascimento, S.A. (1984). *Estudo bioecológico do caranguejo-uçá e das características dos manguezais do estado de Sergipe*. Relatório Técnico da Adema. Aracaju: Governo de Sergipe.

Neto, L.S. (2007). *Escalas de variabilidade espacial na distribuição e densidade do caranguejo Ucides cordatus (Linnaeus, 1763) (Brachyura, Ocypodidae) em manguezais da Baía de Paranaguá (Paraná – Brasil)*. 40 p. Monografia (Graduação) – Universidade Federal do Paraná, Pontal do Paraná, 2007.

Nellmann *et al*. (Eds). (2009). *Blue Carbon. A Rapid Response Assessment. United Nations Environment Programme*. Available in: <http://www.grida.no/publications/rr/blue-carbon>. Accessed at 12/11/12.

Pereira, E. D.; Zaine, J.E. (2007). Mapa geológico-geotécnico da bacia do rio Bacanga - São Luís (MA). *Geociência*s, v. 26, n. 1, 45-54.

Pinheiro. M.A.A. (2006). *Projeto Biologia do caranguejo-uçá Ucides cordatus (Linnaeus, 1763) (Crustacea, Decapoda, Brachyura) no litoral sul de São Paulo – Uçá II*. Relatório Científico, São Vicente: Unesp. 408 p.

Rebelo-Mochel (2003a). Visão da Importância Global dos Manguezais Amazônicos. In: *II Encontro Regional Norte de Educação Ambiental em Áreas de Manguezais (ENEREAM): Transformangue, Saberes e Poderes*, São Luis-MA. Palestra Proferida durante o II Encontro Regional Norte de Educação Ambiental em Áreas de Manguezal. Relatório do Encontro. São Luís.

Rebelo-Mochel (Cord.). (2003b). *Zoneamento Costeiro do Estado do Maranhão*. Coord. (a). Rebelo-Mochel, F. Universidade Federal do Maranhão (UFMA), Universidade Estadual do Maranhão (UEMA), CD-ROOM.

Scavia, D.J.C. *et al.*. (2002). Climate change impacts on U.S. coastal and marine ecosystems. *estuaries* 25*:* 149–164.

Schaeffer-Novelli, Y. *et al.* (2000). Brazil mangroves. *Aquatic Ecosystem Health and Management* Volume 03, Issue 4, 561-570.

Schaeffer-Novelli, Y.; Cintron-Molero, G. & Soares, M.L.G., (2002). Mangroves as indicators of sea-level change in the muddy coasts of the world. *In:* Wang, Y. and Healy, T. (eds.), *Muddy Coasts*. United Kingdom: Elsevier, pp. 245-262.

Schmidt, A.J. (2006). *Estudo da dinâmica populacional do caranguejo-uçá Ucides cordatus cordatus (Linnaeus, 1763) (Crustacea-Decapoda-Brachyura) e dos efeitos de mortalidade em massa dessa espécie em manguezais do sul da Bahia*. 2006. 186 p. Dissertação (Mestrado) – Universidade de São Paulo, São Paulo.

Schmidt, A.J. & Oliveira, M.A. (2006). *Plano de ação para o caranguejo-uçá em Canavieiras*: Alma/Ecotuba/Critical Ecosystem Partnership Fund. 90 pp.

Schmidt, A.J. *et al*. (2004). Levantamento de áreas afetadas por mortalidade em massa do caranguejo-uçá *Ucides cordatus* em manguezais do sul da Bahia. In: *Simpósio Brasileiro de Oceanografia, 2. São Paulo*. Resumos.

Silva Junior, M.G. et al. (2007). Relação peso-comprimento de espécies de peixes do estuário do rio paciência da Ilha do Maranhão, brasil. *Boletim do Laboratório de Hidrobiologia, 20: p. 31-38.*

Spalding, M.; Kainuma, M. & Collins, L. (2011). *World mangrove atlas*. London, Washington D. C. ISBN 978-1-84407-657-4. 319 pp.

INPE (2011). TerraView Software copyright © 2001-2011 INPE, Tecgraf PUC-Rio and FUNCATE. Available in: <http://www.dpi.inpe.br/terraview>. Accessed at 12/11/12.

UEMA. (2000) – *Atlas do maranhão*/gerência de planejamento e desenvolvimento econômico, laboratório de geoprocessamento/Universidade Estadual do Maranhão (LABGEO/UEMA). São Luis: GEPLAN, 36 pp.

Walters B.B. (2008). Ethnobiology, socio-economics and management of mangrove forests: A review. Aquatic botany 89: 220-236.

Well, S. *In the Front Line: Shoreline Protection and Other Ecosystem Services from Mangroves and Coral Reefs*. United Nations Environment Programme World Conservation Monitoring Centre, Cambridge, UK, 2006. 36 p.

Wolfram, S. (1983). Statistical mechanics of cellular automata. *Reviews of Modern Physics*, Vol. 55, No. 3, July.

Wunderlich, A.C.; Pinheiro, M.A.A. & Rodrigues, A.M.T. (2008). Biologia do caranguejo-uçá Ucides cordatus (Crustacea: Decapoda: Brachyura) na Baía da Babitonga, Santa Catarina, Brasil. Revista Brasileira de Zoologia, v. 25, n. 2, 188-198.