Mangrove Response to Land Use Change in Estuaries along the Semiarid Coast of Ceará, Brazil

Authors: Mario Duarte Pinto Godoy, Antônio Jeovah de Andrade Meireles, and Luiz Drude de Lacerda

Source: Journal of Coastal Research, 34(3) : 524-533

Published By: Coastal Education and Research Foundation

URL: https://doi.org/10.2112/JCOASTRES-D-16-00138.1

Journal of Coastal Research	34	3	524–533	Coconut Creek, Florida	May 2018

Mangrove Response to Land Use Change in Estuaries along the Semiarid Coast of Ceará, Brazil

Mario Duarte Pinto Godoy*, Antônio Jeovah de Andrade Meireles, and Luiz Drude de Lacerda

Marine Science Institute
Federal University of Ceará
Fortaleza 60165-081, CE, Brazil

ABSTRACT

Godoy, M.D.P.; Meireles, A.J.A., and Lacerda, L.D., 2018. Mangrove response to land use change in estuaries along the semiarid coast of Ceará, Brazil. *Journal of Coastal Research,* 34(3), 524–533. Coconut Creek (Florida), ISSN 0749-0208.

Mangroves cover an estimated area of approximately 12 to 20 million ha worldwide and serve as protection for the coastline from erosion and flooding. Nearly 70 mangrove species are considered endangered and could disappear in the next decade, which would have devastating economic and environmental consequences for coastal communities because of their ecological and economic importance. The annual rate of disappearance of coastal ecosystems is four times greater than the rate of the disappearance of rain forests. Mangroves suffer great pressure from the rapid conversion of forests into agricultural and urban areas, and, in these scenarios, climate change promotes specific pressures on mangroves and may increase the effects of anthropogenic activities. The focus of this study was to map the changes in mangrove areas in six river estuaries in Ceará, northeastern Brazil, between the years 1992 and 2011 and identify the main drivers of these changes. The results showed an increase in mangrove areas of five estuaries, while one estuary showed a decrease in mangrove area. Changes in river output capacity and sediment accumulation in the estuaries were associated with dam construction in the watersheds and can be responsible for new upstream mangrove areas in newly formed islands and along river banks. Abandoned saltpans also contributed to expansion of the mangrove areas. Deforestation for the construction of shrimp farms was the main cause of decreases in mangrove area, especially in the Pirangi estuary.

ADDITIONAL INDEX WORDS: *Geoprocessing, environmental changes, remote sensing*.

INTRODUCTION

Mangrove forests cover an estimated area of 12 to 20 million ha worldwide (FAO, 2007). The distribution of mangrove forests is restricted to the intertropical zone between latitudes 30° N and 30° S and roughly follows the 20°C marine isotherm that depends on currents and can vary during the summer and winter (Spalding, Blasco, and Field, 1997).

Mangroves serve as coastline protection against erosion and flooding, function as a nursery for species of commercial importance and as a landing area for migratory birds, filter sediments and pollutants, and capture and store carbon (Carvalho Neta, 2007; FAO, 2007; Scavia *et al*., 2002).

The social values of these services are extensive and include reducing the costs and effects of natural disasters, maintaining human health, improving the food security of local communities, and sustaining aesthetic and cultural values. Taking into account the biodiversity of species and the livelihoods of the population dwelling near coastal estuaries, mangroves provide approximately $1.6 billion a year in services. However, because of the high population density of coastal areas, mangroves are under increasing pressure from urban and agricultural expansion, industrial harbors, chemical spills, and eutrophication and hydrological changes in the river watershed (Long *et al*., 2014; Medina *et al*., 2001; Simard, Pinto, and Riddick, 2008; USGS, 2004; Valiela, Bowen, and York, 2001).

Approximately 70 mangrove species are considered at risk of extinction and could disappear in the next decade. This loss would have devastating economic and environmental consequences for coastal communities because of the ecological and economic importance of mangrove forests (Polidoro *et al*., 2010).

Mangroves establish along sedimentary coastlines and intertidal areas of tropical and some subtropical zones. Mangroves undergo physiological and morphological adaptations to cope with environmental stresses, such as a high salinity, a low dissolved oxygen concentration in the water, and mobile substrates (Ellison and Stoddart, 1991). Mangroves also possess the ability to trap and accumulate sediments, generate new areas for sedimentation, and quickly colonize sandbanks and beaches. Therefore, it becomes very important to understand the possible sediment sources to an estuary and how human activities at a river basin affect the sediment load in an estuarine environment. Because human activities change the sediment balance, alterations may occur in the coverage of mangroves and their ecological role in the continent-sea interface.

In this context, the main objective of this study was to use satellite imagery to study changes in the distribution of mangroves in six river estuaries located along the semiarid coast of Ceará, northeastern Brazil, and compare the changes caused by local human intervention.

DOI: 10.2112/JCOASTRES-D-16-00138.1 received 2 August 2016; accepted in revision 17 January 2017; corrected proofs received 20 June 2017.
*Corresponding author: mariodpgodoy@yahoo.com.br

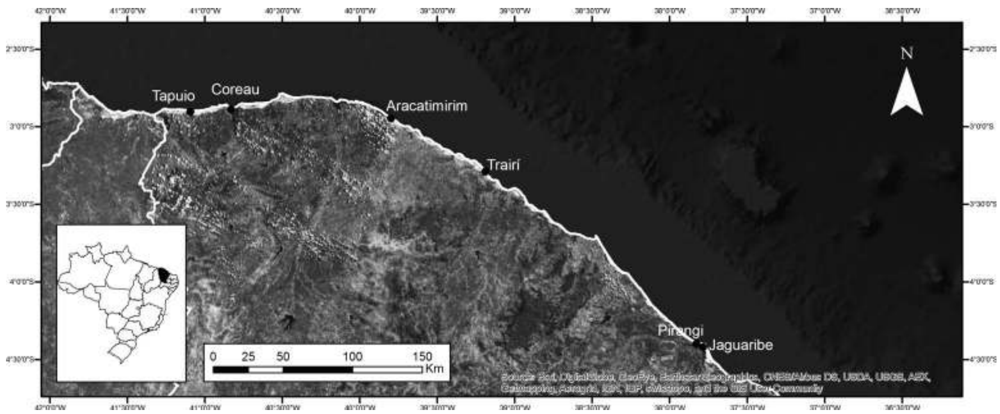

Figure 1. Localization of studied estuaries along the Ceará state coast.

METHODS

This section explains all the steps taken to carry out this work, from the localization of the studied estuaries, choice of images, cover classification process, and what was done to ensure the quality of the results.

Study Area

The study area (Figure 1) is located along the coast of Ceará, northeastern Brazil, and consist of six estuaries: Aracatimirim, Coreaú, Jaguaribe, Pirangi, Tapuio, and Trairí.

The climate of the region is classified as semiarid, and the year is divided into two distinct and well-defined periods: a rainy season from December to May and a dry season that runs from June to November (Dias, 2007).

In addition to this temporal variation is a spatial variation of rainfall between the coastal region and the interior; for example in Aracati, located 14 km from the Jaguaribe River mouth, it rains an average of 982.6 mm/y, and in Itaiçaba, 34 km from the mouth of the Jaguaribe River, the average is 736.9 mm/y.

Satellite Image Acquisition and RGB Composition

They LiveFor this study, Landsat 5 images were used with 30-m spatial resolution. These images were obtained from the website of the Brazilian National Institute for Space Research (INPE, 2015). Images from 1992 to 2011 were obtained, depending on the availability of the images and the amount of cloud cover above the study area during the period of satellite coverage.

Figure 2. Comparison between the classifications without a majority filter (left) and using a majority filter (right), where it is possible to notice the reduction in isolated pixels and the smoothness of the classified area after applying the filter.

The map projection used was the Universal Transverse Mercator (UTM), referenced to the horizontal geodetic datum SIRGAS 2000. The images were georeferenced using reference points and intersections of roads, farms, and other permanent features that could be found in every image used in this study. The root mean square of geoprocessing error was less than 10 m.

In the composition process, RGB bands 3, 4, and 5 were used. Band 5, which corresponds to mid-infrared wavelengths (1.55–1.75 μm), was colored red; band 4, which corresponds to near infrared wavelengths (0.76–0.90 μm), was colored green; and band 3, which corresponds to visible red wavelengths (0.63–0.69 μm), was colored blue.

Land Cover Classification

Image vectorization was performed in ArcGIS 10 (ESRI, Redlands, California, U.S.A.) using a pixel-by-pixel supervised classification methodology. In this methodology, the user defines small areas of the image with known land cover classification, and these areas are referred to as "training areas" based on this classification. Algorithms are used to provide an automated image classification based on the spectral similarity of each pixel to the indicated training areas.

The first step was to create a polygon to demarcate the areas that served as samples in the supervised classification. Because the main objective of this study was limited to understanding the mangrove area, only two classes were created. The first class was the mangrove area, and the second class was every other land cover, including other types of vegetation, dunes, beaches, and surface water.

Several polygon features were created, and a column of classes was added to the attribute table. Features of class 1 referred to the mangrove areas, and features of class 0 referred to any other ground cover.

For the supervised classification, the Maximum Likelihood Classification tool (MAXVER) was used. This methodology was used to perform a pixel-by-pixel supervised

Table 1. *Results from mapping six estuaries along the northeastern Brazilian coast using Landsat 5 imagery.*

	1993	1994	1995	1996	1999	2000	2001	2003	2004	2005	2006	2007	2008
Aracatimirim						0.4		0.59		0.75	0.74		
Coreaú	28.37	27.55				28.78		31.85		28.81	28.41		30.61
Jaguaribe	7.32				5.66		6.42	6.1	5.71		6.78		6.38
Pirangi	2.29				1.11		0.79	1.04	0.99		1.03		1.08
Tapuio		3.91			4.2	4.67		5.4		4.77	4.22		4.32
Trairí			0.36	0.63						0.75		0.53	

classification, and once the classification was performed, a raster file with the results was generated. After the classification, a majority filter tool was used to reduce classification errors, smooth edges, and reduce the number of isolated single pixels. The results of this step are shown in Figure 2.

Minor corrections to the results were made to eliminate polygons that had been classified incorrectly, and the areas of different features were calculated. The results were compiled in maps for each estuary that showed where mangrove areas increased or decreased.

Quality Control

Several tools were used to assess mapping quality. First, a thorough comparison of the results found in this study with the results from several others studies was performed. Additional comparisons between the mapped areas were made using images with better spatial resolution, and field visits were performed to remove eventual doubts that emerged during mapping.

Compared with previous studies, differences were observed of less than 10% for the Coreaú and Jaguaribe rivers, of less than 30% for the Tapuio River, and of more than 30% for the Aracatimirim and Pirangi rivers. No previous study of this type had been performed for the Trairí River. The comparisons showed that, initially, errors were higher in estuaries that had a mangrove area smaller than 1.5 km^2 (the Pirangi estuary). Comparing these results with high-resolution images showed that the methodology used in this study allowed for the delimitation of vegetation and enabled the monitoring of mangrove changes over the years in an acceptable manner, taking into account the spatial resolution of the images.

RESULTS

This section presents the results obtained during this study by first using a more general approach showing how the studied mangroves behaved overall; then, each estuary is presented separately, pointing out the most important aspects found during mapping and field visits.

Mangrove Mapping

Tables 1 and 2 summarize the results from mapping estuaries using Landsat 5 imagery between 1992 and 2011. Five out of six estuaries showed an increase in the mangrove area (the Aracatimirim, Coreaú, Jaguaribe, Tapuio, and Trairí estuaries) from initial mapping to final mapping, and one estuary showed a decrease in the mangrove area (the Pirangi estuary) from initial to final mapping.

The most striking results were from the Aracatimirim estuary, which demonstrated a 400% increase in mangrove area, and from the Pirangi estuary, which lost more than 70% of its mangrove forest cover.

Aracatimirim River

The Aracatimirim River estuary (Figure 3) is near the village of Almofala and was the estuary that showed the largest relative increase in mangrove area (437%); this occurred partially because the initial mangrove coverage was very small (only 0.16 km^2, which was the smallest area within the studied estuaries). However, this increase allowed the Aracatimirim estuary to surpass the Pirangi and Trairí rivers in respect to mangrove area. Mapping showed that the mangrove expansion occurred on newly formed islands and river margins approximately 2 km from the river mouth.

Most of the mangrove areas were located near the river mouth, and changes between 1993 and 2000 were limited to this area (Figure 4). No other mangrove areas further inland could be perceived in the images. However, in the image from 2000, it was already possible to see mangroves in a region that was approximately 7 km from the mouth of the river (Figure 5). This mangrove area grew steadily until 2008, which was the last year of observation.

Several small dams along the river that capture water for economic activities and human consumption have a negative effect on river flow and can contribute to the expansion of

Table 2. *Summary of the results from mapping six estuaries along the northeastern Brazilian coast using Landsat 5 imagery.*

	Initial Area (km^2)	Final Area (km^2)	Difference (km^2)	Difference (%)
Aracatimirim	0.16	0.86	+0.7	+437.5
Coreaú	28.15	30.61	+2.46	+8.7
Jaguaribe	7	7.29	+0.29	+4.1
Pirangi	1.34	0.3	−1.04	−77.6
Tapuio	4.49	4.9	+0.41	+9.1
Trairí	0.36	0.53	+0.17	+47.2

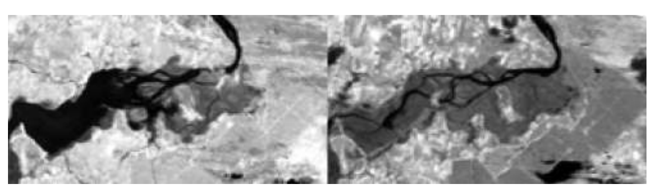

Figure 3. Mangrove changes in the Aracatimirim River estuary between the years 1993 and 2008, where it is possible to notice the increase in mangrove area further inland.

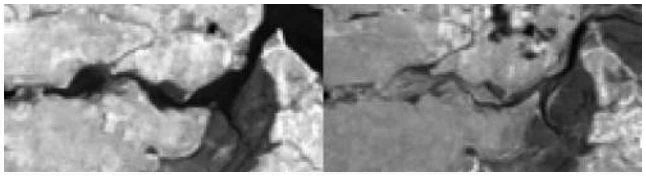

Figure 4. Mangrove growth near the Aracatimirim River mouth between 1993 (left) and 2008 (right), where it is possible to notice the emergence of mangrove areas in sandbanks.

mangrove areas with the creation of new islands and the expansion of beaches along the margins of the river.

The main sources of anthropogenic effects in this region are coconut and salt production in the estuary and, sometimes, in the mangrove areas (Figure 6); the original vegetation was removed to conduct these activities, as shown in Figure 6.

Several communities located on the riverbanks use mangroves for fuel and raw material for the construction of houses and use the area for subsistence agriculture and livestock grazing (Silva and Souza, 2006).

Although shrimp farms are also in the region, this activity is still incipient. Because of its intrinsic economic value and the increasing search for new areas for shrimp farms, it is necessary to create better control methods.

Coreaú River

The Coreaú River (Figure 7) contains the largest mangrove area in this study. In 1992, the Coreaú River estuary had 28.15

Figure 6. Coconut plantations and salt pans in mangrove areas along the Aracatimirim estuary. Both are common economic practices in the region and are responsible for the decrease on mangrove forest in some areas.

km^2 of mangrove area, and in 2008, it had 30.61 km^2, which is an increase of 2.46 km^2, or approximately 8.7%.

Despite influence from the city of Camocim and the expansion of shrimp farming, this estuary showed little decrease in mangrove area. Vegetation expanded over abandoned salt pans, many of which were utilized to cultivate shrimp, but several salt pans remained abandoned and were colonized by mangroves (Figure 8).

Jaguaribe River

The Jaguaribe River (Figure 9) is the largest river in Ceara, and its watershed covers almost 50% of the state. Along its course, a wide range of activities takes place, including the largest shrimp farms in the state. A study conducted by Godoy

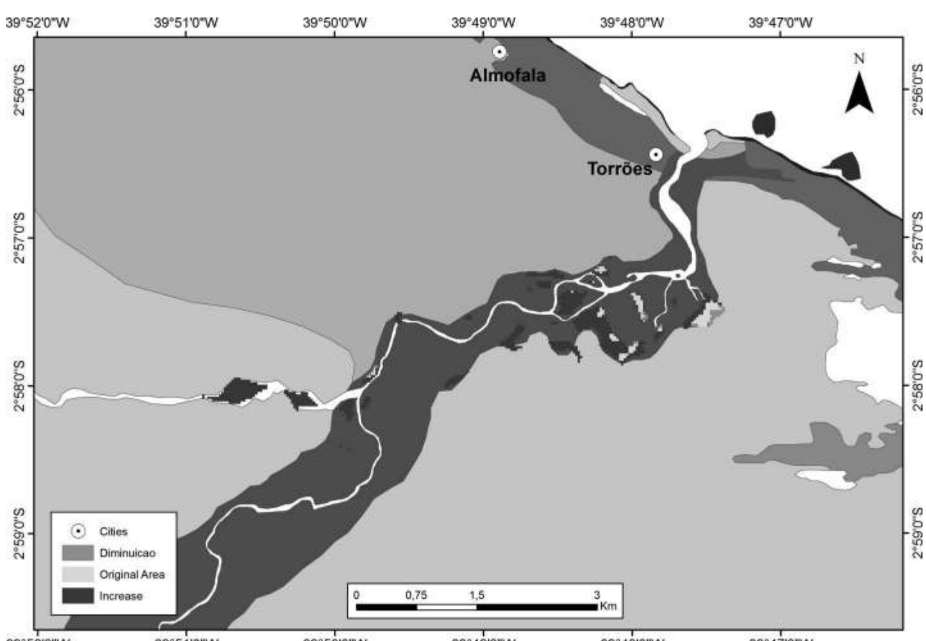

Figure 5. Mangrove growth inland of the Aracatimirim River mouth between 1993 (left) and 2008 (right) as a result of saline intrusion and reduction of fresh water input caused by damming.

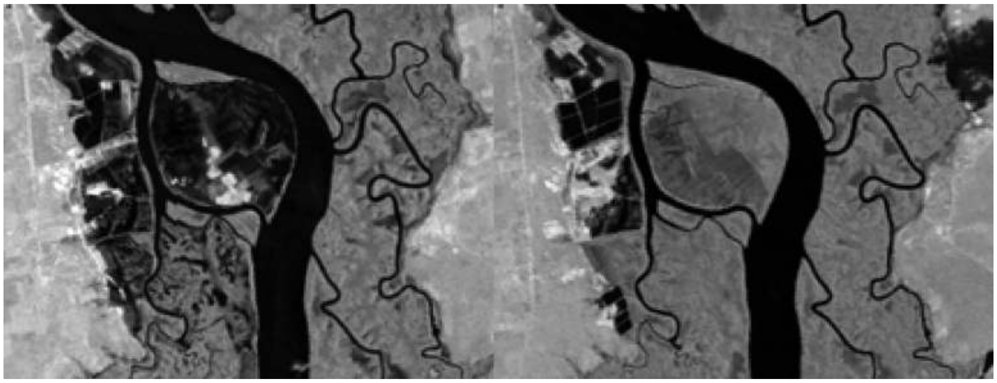

Figure 7. Mangrove changes in the Coreaú River estuary between 1993 and 2008, where it is possible to notice the increase of mangrove in an island located inside the estuary where there was an old salt pan and the new shrimp farms near the mangrove vegetation.

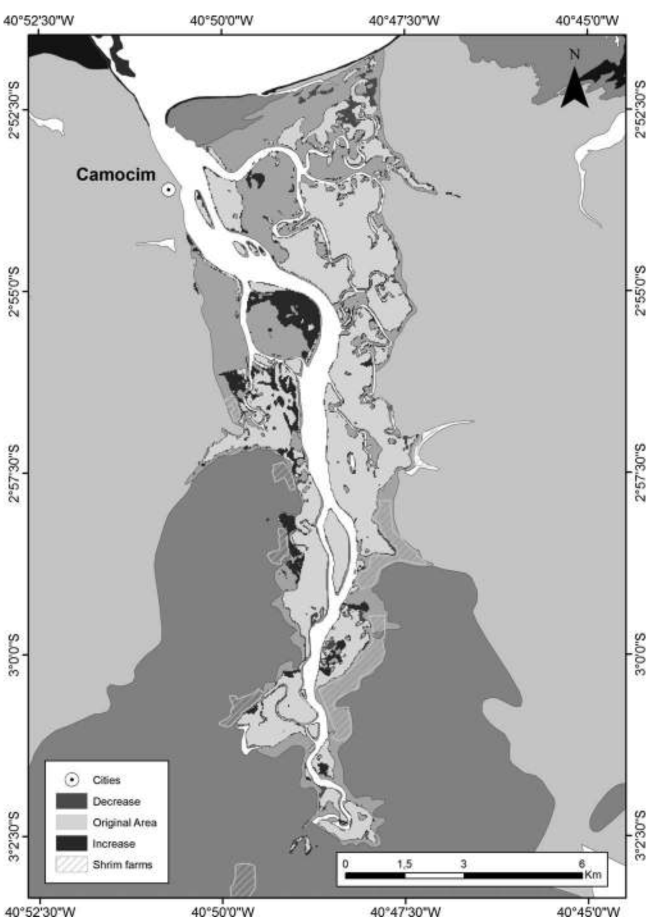

Figure 8. Mangrove growth in abandoned salt pans of the Coreaú River between 1993 (left) and 2008 (right). The high groundwater salinity in these areas make them inhospitable for most vegetation; however, the mangrove is capable of colonizing these areas by natural adaptations.

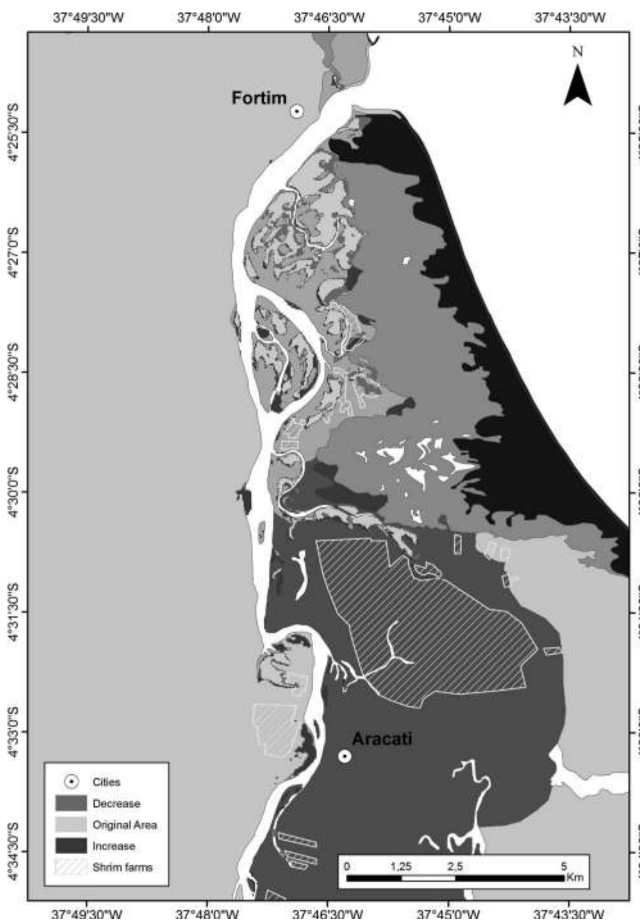

Figure 9. Mangrove changes in the Jaguaribe River estuary between 1992 and 2010, where it is possible to notice the largest shrimp farm in Ceará and the newly formed mangrove areas farther inland and on islands in the estuary.

Figure 10. Mangrove growth on an island in the Jaguaribe River estuary between 2009 (left) and 2010 (right) shows clearly how fast the mangrove colonization process is.

and Lacerda (2014) surveyed these areas and found approximately 20 km^2 of shrimp farming had been implemented in the estuary since 1992.

Several increases in mangrove areas in newly formed islands in the estuary (Figure 10) were found. This phenomenon of island formation was also studied by Godoy and Lacerda (2014), and they found that the emergence of new islands in the estuary accounted for an increase in land area of 24.15 ha from 1988 to 2010.

Another mangrove growth area occurred along the river bank above the town of Aracati, approximately 14 km from the mouth of the river. These mangrove areas did not previously exist in this location and began to appear in images from 2006, with 4 ha, and increased in 2010 to 22 ha (Figure 11).

This mangrove expansion further inland may be due to the advance of marine water in the underground water supply because of the construction of dams along the river. Marins *et al.* (2003) showed that salinity at the city of Itaiçaba advanced 34 km from the mouth of the river and that salinity was constant and higher than sea water. This high concentration of salt in regions that were once fresh has also enabled the advance of mangroves in areas where it was previously impossible for them to grow. This expansion occurred at the expense of other species that are less well adapted to high salinity.

Pirangi River

The Pirangi River suffers greatly from human pressure. Over the years, large areas of the estuary were converted into salt pans and, later, shrimp farms, resulting in a highly affected estuary with highly fragmented mangrove areas. In 1992, there were only 1.34 km^2 of mangroves, and by 2011, approximately 70% of this vegetation had disappeared from the estuary, or around 1.4 km^2 (Figure 12).

Small areas of mangrove growth were found near the mouth of the Pirangi River. These areas were mostly sand banks and abandoned salt pans (Figure 13). In addition to this growth, most of the mangroves of this estuary have disappeared because of human activity, as shown in Figure 14.

Tapuio River

Like many estuaries in Ceará, the Tapuio River (Figure 15) also has salt pans and shrimp farms; however, unlike the Pirangi River and other rivers in this study, these activities had little effect on mangrove vegetation, at least in a way that was recorded by satellite images. In 1992, mangroves covered approximately 4.5 km^2, and in 2010, 4.9 km^2 of this type of vegetation was present around the estuary.

Unlike other estuaries, mangrove area did not clearly increase or decrease; changes occurred across most of the estuary and added up to approximately 0.4 km^2 of expansion, or a 9% increase over 18 years. Small mangrove increases occurred near the mouth of the river, especially on the left arm. Most of the increase was caused by recolonization of abandoned salt pan within mangrove areas. Mangrove growth was hindered because the rest of the area was again used for salt production (Figure 16), and decreases in growth occurred along the estuary, mainly at mangrove borders or because of the disappearance of small areas of mangroves.

Trairí River

The Trairí River estuary (Figure 17) had a small mangrove area, which in 1995 was 0.36 km^2 and in 2007 had increased to 0.56 km^2, an increase of 0.17 km^2, or 47%. It is possible to notice that this estuary has a high concentration of salt in the water, which evaporates during the dry season and creates a layer of salt on the sediment.

Like many rivers in the state, the flow of the Trairí River is also controlled by dams. The main dam located in the Trairí watershed regularized water flow at 0.63 m^3/s (SRH, 2014). The regularization of the river may partly explain the increase in mangroves in the estuary, which was already hypersaline.

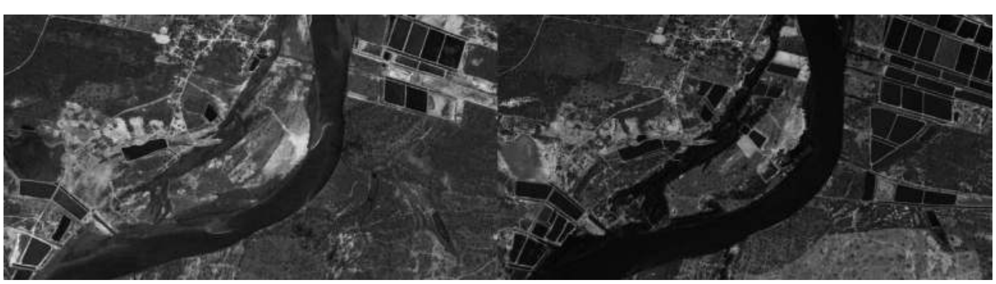

Figure 11. Mangrove areas near the city of Aracati at the Jaguaribe River between 2003 (left) and 2013 (right). In this figure, it is possible to notice mangrove growth near a city located 17 km from the river mouth where, before the construction of dams along the river, there was no mangrove.

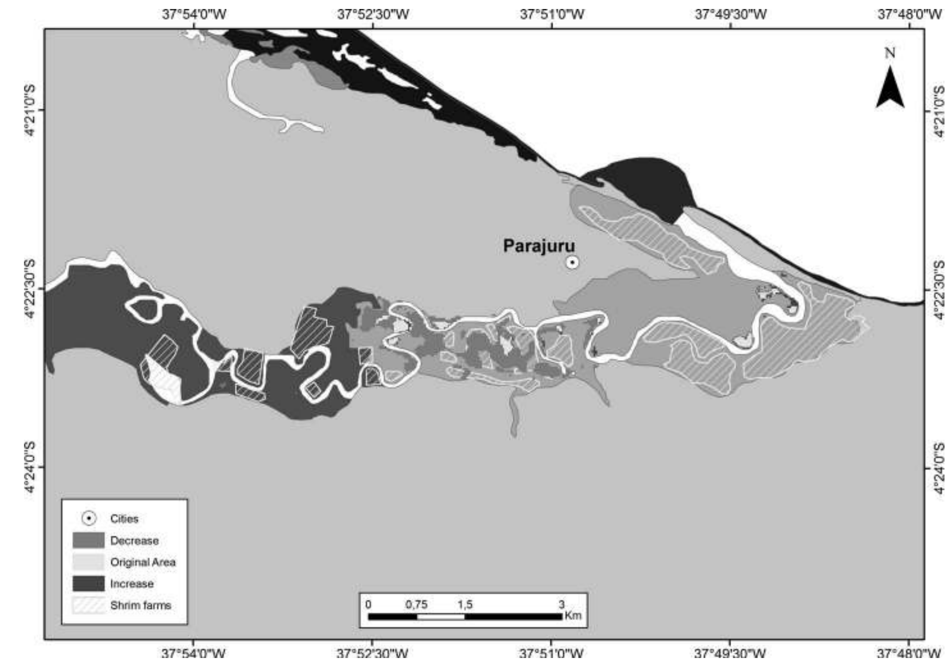

Figure 12. Mangrove change between 1992 and 2011 in the Pirangi River estuary, where it is possible to notice the near complete extinction of mangrove areas on the estuary over the study period.

In the estuarine margins, houses and farms use the vegetation as fuel. Areas with grass are used as pasture, and these areas are close to mangrove vegetation. The herding of animals and their effect on the soil and vegetation may prevent mangroves from expanding over to these areas of pasture.

DISCUSSION

The results show clear changes in mangrove expansion in estuaries, resulting from changes made in the watershed and the estuary. Changes in river flow and land use caused both negative (erosion) and positive (sediment accretion, recolonization) effects on the mangroves. Shrimp farms are the exception, with mostly negative impacts, such as deforestation and decreased water quality in the estuary.

The availability of water for human consumption and economic activities has always been a problem in Ceará; therefore, dam construction has always been present in the state. An example of this policy is the Cedro Dam, which was built between 1880 and 1890 (DNOCS, 2015). According to Companhia de Gestão dos Recursos Hídricos (COGERH, 2015), 149 dams are monitored throughout the state. The effects of damming on fluvial fluxes were discussed by Godoy and Lacerda (2014) in a study that compared monthly rainfall with average river flow in stations located below Castanhão, the largest dam in the state, and it was demonstrated that even in very rainy months, river flow showed no major changes. The exceptions were the years of 2008 and 2009 when the dam had to open its floodgates to prevent structural damage; in those moments, river flow reached higher peaks than those that occurred before dam construction.

Decreased river flow is a result of dam construction and water diversion for economic activities have resulted in the loss of sediment export capacity of rivers. This decrease in flow can generate sediment accumulation in the estuaries, forming new islands and sandbars that are colonized by mangroves. This phenomenon may explain the appearance of islands in the Aracatimirim and Jaguaribe rivers, because all the rivers in this study had dams built along their courses.

Decreased flow from dam building also can trigger erosive processes in the estuarine mouth from an increased tidal influence in the estuary and cause a severe decrease in continental sediment input. This phenomenon was observed specifically in the Jaguaribe River estuary and had been previously reported by Farias and Maia (2009). This phenomenon has also been reported in other countries, such as India (Raha *et al*., 2012) and Thailand (Thampanya *et al*., 2006).

Increasing tidal influence in the estuaries and decreasing freshwater input can cause the advancement of mangroves further inland along riverbanks. This phenomenon occurs

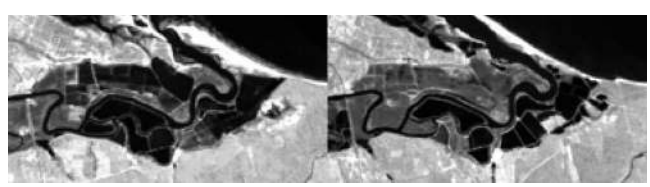

Figure 13. Small mangrove growth near the Pirangi River mouth between 1992 (left) and 2011 (right) and growth of salt pans and shrimp farms.

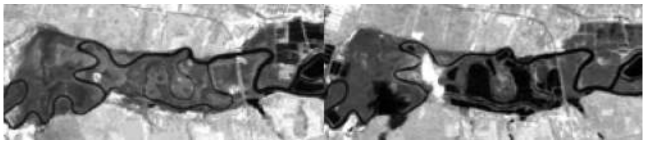

Figure 14. Mangrove deforestation and the creation of salt pans and shrimp farms between 1992 (left) and 2011 (right) along the Pirangi River.

because of the advance of salt water in the river and saline intrusion into soil and groundwater and has been reported in other countries, such as Venezuela (Colonnello and Medina, 1998; Echezuría *et al*., 2002) and Australia (Williamson and Boggs, 2011). This phenomenon was observed in the mapping of the Aracatimirim and Jaguaribe rivers.

The Aracatimirim, Coreaú, and Pirangi estuaries showed mangroves occupying abandoned saline areas, which is common in the region and has been observed in previous studies (Lacerda, Menezes, and Molisani, 2007; Meireles,

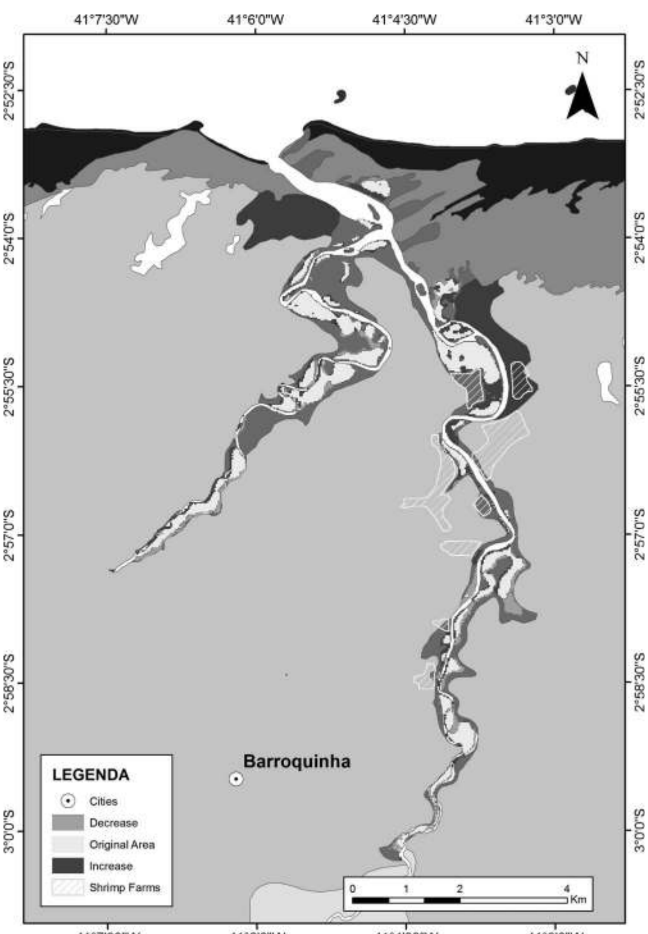

Figure 15. Mangrove changes between 1992 and 2010 in the Tapuio River estuary showing the increase of mangrove in old salt pans and mangrove decrease along the borders of the vegetated areas.

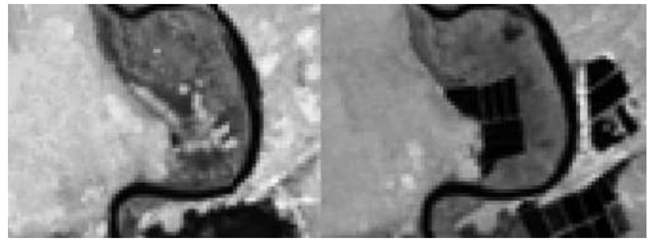

Figure 16. Mangrove occupying abandoned salt pans along the Tapuio River, which is only possible because of high salt concentration in the ground water.

Silva, and Thiers, 2010; Reis-Neto, Meireles, and Cunha-Lignon, 2013). High salt concentrations in soil and groundwater at these sites prevent colonization by other types of vegetation that have no way to remove excess salt. According to Meireles, Silva, and Thiers (2010), the leaching of minerals during tides and freshwater flow from the aquifer, rain, and river are responsible for the decrease in salinity that allows mangroves to occupy these old salt production areas.

Shrimp farms in the Coreaú, Jaguaribe, Pirangi, and Tapuio estuaries are largely responsible for the decrease in mangroves, particularly in the case of the Pirangi River, which had only 30% of its original mangroves left. Previous studies in Ceará estuaries corroborate this finding. Several authors (Figueiredo *et al*., 2005; Lacerda *et al*., 2006; Meireles *et al*., 2007; Meireles, Silva, and Thiers, 2010; Nascimento and Sassi, 2001; Smith III *et al*., 2013) have demonstrated the effects of deforestation, erosion of river banks, siltation, the introduction of chemicals, and eutrophication on mangroves.

The largest shrimp farm in the state is located at the margin of the Jaguaribe River estuary. It was partially built within mangrove areas and caused serious damage to vegetation from deforestation, fragmentation, occupation of expanding areas, soil impermeabilization, and erosion (Meireles *et al*., 2007).

The negative effects of shrimp farms have been abundantly demonstrated in the literature, especially in Asia and Africa. A study by Long *et al*. (2014) showed a 10% decline in mangrove area in the Philippines because of conversion to aquaculture. The situation is similar in countries such as Vietnam, Myanmar, and India (Nguyen, 2014; Raha *et al*., 2012, 2013).

Apart from directly destroying the mangroves, the implementation of these projects also caused changes in the quality of the estuarine water. Studies carried out in the estuary have shown that dissolved oxygen rates and pH are outside the limits established by Brazilian environmental law, according to CONAMA Resolution 357/2005 (Góes D'Assumpção *et al*., 2007).

The removal of mangrove vegetation for urban expansion was also perceived in some of the studied estuaries. In the Jaguaribe River estuary, the occupation of these areas was not

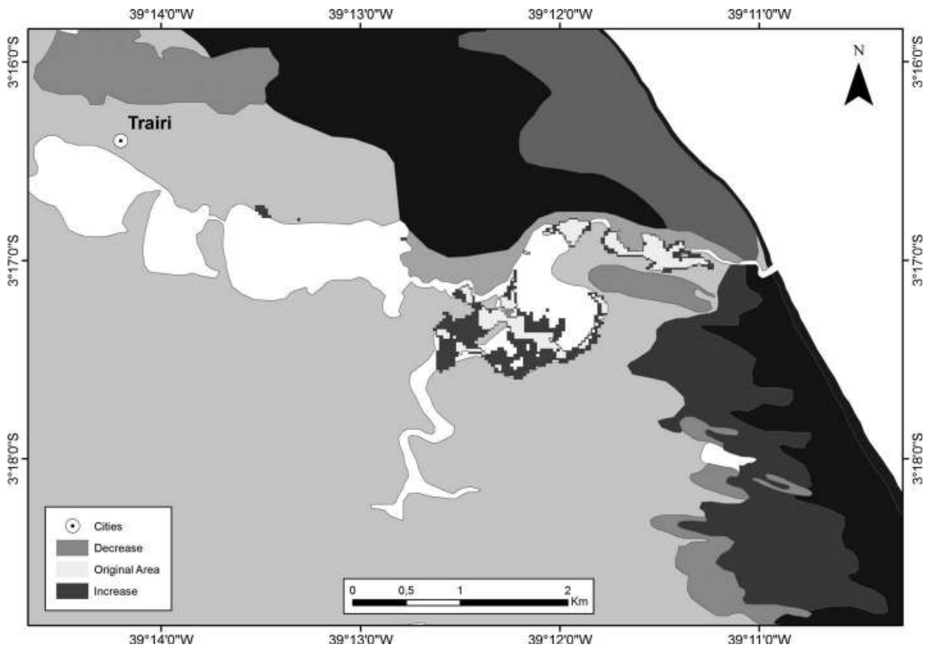

Figure 17. Mangrove changes in the Trairí River estuary between 1997 and 2005, where it is possible to notice the increase of mangrove area inside of the estuary, mainly because of high salinity caused by the high evaporation rates in this location.

limited to a social class, because it was possible to observe both shacks and luxury homes occupying the river banks.

The use of the estuary for agriculture and husbandry was noted in some cases, such as in the Aracatimirim River, where it was possible to observe coconut production in the satellite images; this practice was confirmed in the literature (Silva and Souza, 2006). In the Trairí River, the estuary was used as a grazing area for livestock. A study performed by Silva and Souza (2006) also noted the use of mangrove areas for agriculture and livestock in the Jaguaribe River estuary.

Despite human activities that negatively affect mangrove areas in the studied estuaries, such as shrimp farming, urban expansion, and agriculture, overall, mangrove areas increased from 41.5 to 44.5 km^2. This increase was mainly in old salt pans and islands and sandbanks; this behavior was expected and was previously reported in the literature. However, human activities, especially dam construction, make it difficult to separate the responses of mangrove forests to changes; specifically, it is difficult to separate responses to global climate change from responses to human activities, because these changes act synergistically.

CONCLUSIONS

On the basis of the results presented here, it is possible to conclude that anthropogenic changes in estuaries and watersheds are able to affect in a direct and indirect manner the extension of mangrove forests.

In the presented cases, the formation of sandbanks and islands caused by sediment accumulation inside the estuary because of decreased river flow caused by the construction of dams and the colonization of abandoned salt pans were found to be the main factors causing the increase in mangrove area. Deforestation for the establishment of shrimp farms or other uses by the local population are among the factors that caused a decrease in this type of vegetation within the estuary. Overall, that the studied mangroves have shown an increase in area was an unexpected trend; however, it is a trend followed by others mangrove forests across the world.

Finally, it is possible that global climate change will be able to act in synergy with these anthropogenic changes, increasing their positive and negative effects on the mangroves. Because of a lack of studies, local data, and the number of vectors that affect the estuarine dynamics and, consequently, the mangroves, it becomes very difficult to tell in a concrete manner how these changes will affect this type of vegetation.

ACKNOWLEDGMENTS

This paper is the result of a doctoral thesis and postdoctoral work and would not have been possible without student grants from Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and Fundação Cearense de Apoio ao Desenvolvimento Científico e Tecnológico (Funcap).

LITERATURE CITED

Carvalho Neta, M.L., 2007. Evolução Geomorfológica Atual e Análise da Foz do Rio Jaguaribe, Ceará. Benfica, Fortaleza, Brazil: Universidade Federal do Ceará, Master's thesis, 123p.

COGERH (Companhia de Gestão dos Recursos Hídricos), 2015. *Portal hidrológico do Ceará*. http://www.hidro.ce.gov.br/.

Colonnello, G. and Medina, E., 1998. Vegetation changes induced by dam construction in a tropical estuary: The case of the

Mánamo River, Orinoco Delta (Venezuela). *Plant Ecology*, 139(2), 145–154.

Dias, F.J.S., 2007. Hidrodinâmica das Descargas Fluviais para o Estuário do Rio Jaguaribe (CE). Benfica, Fortaleza, Brazil: Universidade Federal do Ceará, Master's thesis, 111p.

DNOCS (Departamento Nacional de Obras Contra as Secas), 2015. *Açude Cedro*. http://www.dnocs.gov.br/barragens/cedro/cedro.htm.

Echezuría, H.; Córdova, J.; González, V.; Méndez, J., and Yanes, C., 2002. Assessment of environmental changes in the Orinoco River delta. *Regional Environmental Change,* 3(1), 20–35.

Ellison, J.C. and Stoddart, D.R., 1991. Mangrove ecosystem collapse during predicted sea-level rise: Holocene analogues and implications. *Journal of Coastal Research*, 7(1), 151–165.

FAO (Food and Agriculture Organization of the United Nations), 2007. The World's Mangroves 1980–2005. Rome: FAO, *FAO Forestry Paper 153*, 77p.

Farias, E.G.G. and Maia, L.P., 2009. Aplicação de técnicas de geoprocessamento para a análise da evolução da linha de costa em ambientes litorâneos do estado do Ceará. *Anais XIV Simpósio Brasileiro de Sensoriamento Remoto* (Natal, Rio Grande do Norte, Brazil, Ministry of Science and Technology [MCT], National Institute of Space Research [INPE], Society of Latin American Specialists in Remote Sensing [SELPER]), pp. 4585–4592.

Figueiredo, M.C.B.; Araújo, L.F.P.; Gomes, R.B.; Rosa, M.F.; Paulino, W.D., and Morais, L.F.S., 2005. Impactos ambientais do lançamento de efluentes de carcinicultura em águas interiores. *Engenharia Sanitária e Ambiental,* 10(2), 167–174.

Godoy, M.D.P. and Lacerda, L.D., 2014. River-island response to land-use change within the Jaguaribe River, Brazil. *Journal of Coastal Research*, 30(2), 399–410.

Góes D'Assumpção, A.L.; Almeida, M.M.M.; De Paula, D.P.; Lima, Y.C.P., and Alexandre, A.M.B., 2007. Qualidade da água no estuário do Rio Pirangi—CE. *XVII Simpósio Brasileiro de Recursos Hídricos* (São Paulo, Brazil, Associação Brasileira de Recursos Hídricos), pp. 1–16.

Instituto Nacional de Pesquisas Espaciais. *Catálogo de Imagens*. http://www.dgi.inpe.br/CDSR/.

Lacerda, L.D.; Maia, L.P.; Monteiro, L.H.U.; Souza, G.M.; Bezerra, L.J.C., and Menezes, M.O.T., 2006. Manguezais do Nordeste e mudanças ambientais. *Ciência Hoje,* 39(229), 24–29.

Lacerda, L.D.; Menezes, M.O.T., and Molisani, M.M., 2007. Changes in mangrove extension at the Pacoti River estuary, CE, NE Brazil due to regional environmental changes between 1958 and 2004. *Biota Neotropica,* 7(3), 1–7.

Long, J.; Napton, D.; Giri, C., and Graesser, J., 2014. A mapping and monitoring assessment of the Philipinne's mangrove forests from 1990 to 2010. *Journal of Coastal Research,* 30(2), 260–271.

Marins, R.V.; Lacerda, L.D.; Abreu, I.M., and Dias, F.J.S., 2003. Efeitos da açudagem no Rio Jaguaribe. *Ciência Hoje,* 33(197), 66–70.

Medina, E.; Fonseca, H.; Barboza, F., and Francisco, M., 2001. Natural and man-induced changes in a tidal channel mangrove system under tropical semiarid climate at the entrance of the Maracaibo lake (Western Venezuela). *Wetlands Ecology and Management,* 9(3), 233–243.

Meireles, A.J.A.; Cassola, R.S.; Tupinambá, S.V., and Queiroz, L.S., 2007. Impactos ambientais decorrentes das atividades da carcinicultura ao longo do litoral cearense, nordeste do Brasil. *Mercator*, (6)12, 83–105.

Meireles, A.J.A.; Silva, E.V., and Thiers, P.R.L.T., 2010. Impactos ambientais das atividades de carcinicultura no ecossistema Manguezal do Estado do Ceará, nordeste do Brasil. *Revista de Gestão Costeira Integrada*, (4)2, 59–78.

Nascimento, M.S.V. and Sassi, R., 2001. Interferência na área de influência direta do manguezal dos rios Timonha/Ubatuba, Estado do Piauí, Brasil. *Revista Nordestina de Biologia*, 15(2), 73–90.

Nguyen, H., 2014. The relation of coastal mangrove changes and adjacent land-use: A review in Southeast Asia and Kien Giang, Vietnam. *Ocean & Coastal Management*, 90, 1–10.

Polidoro, B.A.; Carpenter, K.E.; Collins, L.; Duke, N.C.; Ellison, A.M.; Ellison, J.C.; Farnsworth, E.J.; Fernando, E.S.; Kathiresan, K.; Koedam, N.E.; Livingstone, S.R.; Miyagi, T.; Moore, G.E.; Nam, V.N.; Ong, J.E.; Primavera, J.H.; Salmo, S.G., III; Sanciangco, J.C.; Sukardjo, S.; Wang, Y., and Yong, J.W.H., 2010. The loss of species: Mangrove extinction risk and geographic areas of global concern. *PLoS ONE,* 5, 1–10.

Raha, A.; Das, S.; Banerjee, K., and Mitra, A., 2012. Climate change impacts on Indian Sunderbans: A time series analysis (1924–2008). *Biodiversity and Conservation*, 21(5), 1289–1307.

Rao, M.; Htun, S.; Platt, S.G.; Tizard, R.; Poole, C.; Myint, T., and Watson, J.E.M., 2013. Biodiversity conservation in a changing climate: A review of threat and implications for conservation planning in Myanmar. *Ambio*, 42(5), 789–804.

Reis-Neto, A.S.; Meireles, A.J.A., and Cunha-Lignon, M., 2013. Analyses of the mangrove's rehabilitation process in abandoned saltwork area, in the Ceará River, northeastern Brazil. *International Journal of Applied and Natural Sciences*, 2(5), 27–36.

Scavia, D.; Field, J.C.; Boech, D.F.; Buddemeier, R.W.; Burkett, V.; Cayan, D.R.; Fogarty, M.; Harwell, M.A.; Howarth, R.W.; Mason, C.; Reed, D.J.; Royer, T.C.; Sallenger, A.H., and Titus, J.G., 2002. Climate change impacts on U.S. coastal and marine ecosystems. *Estuaries*, 25(2), 149–164.

Silva, E.V. and Souza, M.M.A., 2006. Principais formas de uso e ocupação dos manguezais do Estado do Ceará. *Caderno de Cultura e Ciência*, 1(1), 12–20.

Simard, M.; Pinto, N., and Riddick, S., 2008. Characterizing vegetation 3D structure globally using spaceborne lidar and radar. *Eos, Transactions American Geophysical Union,* 89(53), Fall Meeting Supplement, Abstract B41C-0402.

Smith, T.J., III; Foster, A.M.; Tiling-Range, G., and Jones, J.W., 2013. Dynamics of mangrove-marsh ecotones in subtropical coastal wetlands: Fire, sea-level rise, and water levels. *Fire Ecology*, 9(1), 66–77.

Spalding, M.; Blasco, F., and Field, C.D., 1997. *World Atlas of Mangrove*. Okinawa, Japan: The International Society for Mangrove Ecosystems, 178p.

SRH (Secretaria Recursos Hídricos), 2014. *Atlas eletrônico dos recursos hídricos do Ceará*. http://atlas.srh.ce.gov.br/.

Thampanya, U.; Vermaat, J.E.; Sinsakul, S., and Panapitukkul, N., 2006. Coastal erosion and mangrove progradation of Southern Thailand. *Estuarine, Coastal and Shelf Science*, 68(1–2), 75–85.

USGS (U.S. Geological Survey), 2004. *Global change impacts on mangrove ecosystems*. Lafayette, Louisiana: U.S. Department of the Interior, *Fact Sheet 2004,* 3125p.

Valiela, I.; Bowen, J.L., and York, J.K., 2001. Mangrove forest: One of the world's threatened major tropical environments. *BioScience*, 51(10), 807–815.

Williamson, G.J. and Boggs, G.S., 2011. Late 20th century mangrove encroachment in the coastal Australian monsoon tropics parallels the regional increase in woody biomass. *Regional Environmental Change*, 11(1), 19–27.