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## **Mangroves Response to Climate Change: A Review of Recent Findings on Mangrove Extension and Distribution**

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### **ABSTRACT**

Mangroves function as a natural coastline protection for erosion and inundation, providing important environmental services. Due to their geographical distribution at the continent-ocean interface, the mangrove habitat may suffer heavy impacts from global climate change, maximized by local human activities occurring in a given coastal region. This review analyzed the literature published over the last 25 years, on the documented response of mangroves to environmental change caused by global climate change, taking into consideration 104 case studies and predictive modeling, worldwide. Most studies appeared after the year 2000, as a response to the 1997 IPCC report. Although many reports showed that the world's mangrove area is decreasing due to direct anthropogenic pressure, several others, however, showed that in a variety of habitats mangroves are expanding as a response to global climate change. Worldwide, pole ward migration is extending the latitudinal limits of mangroves due to warmer winters and decreasing the frequency of extreme low temperatures, whereas in low-lying coastal plains, mangroves are migrating landward due to sea level rise, as demonstrated for the NE Brazilian coast. Taking into consideration climate change alone, mangroves in most areas will display a positive response. In some areas however, such as low-lying oceanic islands, such as in the Pacific and the Caribbean, and constrained coastlines, such as the SE Brazilian coast, mangroves will most probably not survive.

**Key words:** climate, mangrove, limits, migration.

### **INTRODUCTION**

Mangroves are forest formations estimated to cover from 12 to 20 million hectares worldwide (FAO 2007). Mangrove distribution restricts to the intertropical zone, between 30° N and 30° S latitudes and roughly follows the 20 °C isotherm of seawater temperature, which in turn depends on sea currents and therefore can vary between winter and summer (Spalding et al. 1997).

Natural coastal habitats such as salt marshes, mangroves, coral and oyster reefs, and seagrass beds, buffer coastlines from erosion and inundation, providing important protective services. One of the many advantages of nature-based protection is that those same habitats also provide other benefits, including nursery grounds for commercially and recreationally valued species, landing point for migratory birds, filtration of sediment and pollutants, and carbon storage and sequestration (FAO 2007, Scavia et al. 2002).

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The social values of these services are broad and include those reflected in markets, such as diminishing the costs of natural disasters, maintaining human health and livelihoods through improving food security, and sustaining cultural and aesthetic values. Based on biodiversity alone, mangrove forests provide at least US \$1.6 billion each year in ecosystem services and support of coastal livelihoods worldwide (Polidoro et al. 2010). However, by occupying the coastline, which includes areas of high population density, mangroves are under constant pressure from urban and agricultural expansion, diverse industrial activities, hydrological changes of river basins, spills of chemicals and eutrophication, despite its great importance in sustaining the coastal zone (Medina et al. 2001, Valiela et al. 2001, USGS 2004, Long et al. 2014).

Studies to assess the extinction risks of mangrove species found that 70 species of mangroves, mostly in Asia and Oceania, stand at elevated threat of extinction and could disappear within the next decade. This loss will have devastating economic and environmental consequences for coastal communities due to the importance of these species for the livelihood of indigenous populations (Polidoro et al. 2010).

Climate change has been receiving increasing awareness relative to its potential impacts on the coastal zone, generally associated with sea level rise, increase in air and water temperature, increase in atmospheric CO<sub>2</sub>, alterations in the quantity and quality of the continental runoff and changes in the frequency and intensity of extreme meteorological events (Alongi 2008). Because of their location at the continent-ocean interface, mangroves are more likely to respond to these hazards resulting from global climate change. All of these will, to some extent, alter primary and secondary productivity and respiration of mangroves and their associated biocoenosis, and the transport of materials to adjacent terrestrial and marine ecosystems.

Latest estimates suggest that it is very likely that sea level will rise in 95% of the coastal areas worldwide, with changes varying from 0.26 m in the more optimistic models to 0.98 m in the most pessimistic projections (IPCC 2013). The past 20 years have witnessed a global mean sea level rise of  $3.23 \pm 0.4 \text{ mm yr}^{-1}$ . However, high regional variability stretches this mean one order of magnitude; in fact the western coasts of North America Western witnessed a fall by  $1\text{-}2 \text{ mm yr}^{-1}$ , while rising by  $5\text{-}20 \text{ mm yr}^{-1}$  in SE Asia and the Western Pacific (Nicholls and Cazenave 2010). Best-case scenarios suggest an average sea level rise by 2081-2100 of 40 cm (26-55 cm) (whereas worst-case scenarios anticipate an average of 63 cm (45-82 cm); relative to 1986-2005. This rise will not be uniform across regions and about 70% of the global coastline will experience a change of  $\pm 20\%$  of the global mean (Pachauri 2015). Therefore, mangrove response to these changes will likely to vary regionally.

Although changes in sea levels are the most obvious threat to mangroves, for an individual stand, the relative mean sea level (the difference at that point in space and time between the mean global sea level and the local isostatic change due to glacial rebound) (Nicholls and Cazenave 2010) will be the key variable inducing the specific mangrove response. Direct human drivers that affect the sediment budget of mangroves and thus the rise or fall of the mangrove substrate level (e.g. land-use changes, dams, pumping of groundwater, petroleum and gas exploration in deltas, aquaculture) will also influence mangrove response to climate changes, since they result in increasing surface and belowground water salinity, the hydrodynamics of river basins, the amount of sediment reaching the coast, and therefore the erosion-sedimentation equilibrium of the coastline; as well as the mobilization of nutrients and pollutants in estuaries (Scavia et al. 2002, Godoy and Lacerda 2014, Lacerda et al. 2013). In summary,

worldwide, the final impact on mangroves varies according to location, and results from a complex interaction between rising sea level and changes in the watershed, including the decrease of the continental runoff due to altered rainfall regime (Dai et al. 2009).

Within this context, this article aims to analyze recent results from studies done around the world over the past 25 years, on the long-term observation of mangrove's response to anthropogenic induced global climate change. This review takes into consideration case studies and predictive modeling, published between 1991 and 2015, on mangrove forest area and shape changes, latitudinal migration and displacement, along the continent-ocean interface. It is important to note, that although studies on potential or expected response of mangroves to climate change are relatively abundant, we restricted our analysis on actual observed responses. Furthermore, not included in this review are those studies, which focused on the changes in biodiversity and/or in the physiology of mangroves or alterations of environmental biogeochemical processes, although both may be a consequence from changes in the mangrove distribution due to the unique biochemistry of the mangrove environment.

## RESULTS

Based on the number of published articles, found during our survey, on mangrove forest area and shape alterations associated with climate change, there is a growing interest since 1991, when one of the first published paper on the subject appeared (Ellison and Stoddart 1991). However, it is important to note that mangrove response to global changes in the past, such as sea level rise due to deglaciation, has been a source of important data (Castro et al. 2013). The result of Ellison and Stoddart (1991) study paleo-ecology research is frequently in use to support models of mangrove response to anthropogenic climate change. Extensive discussions on the topic can be

found, for example, in Snedaker et al. (1994) for the Florida coast in the USA; Behling et al. (2001, 2004), Toledo et al. (2008a, b) and Guimarães et al. (2010) for the north coast of Brazil; Tessler and Mahiques (1998), Bastos et al. (2010), Barth et al. (2006) and Cunha-Lignon et al. (2009) for Southeastern Brazil and Schaeffer-Novelli et al. (2002) for a global review on the interactions between mangroves and sea levels.

The interest in the subject of mangrove response to global climate change began to increase in the early 2000s, probably because of the 1997's IPCC report on climate change (IPCC 1997) and of the previous report from UNEP-UNESCO on the expected impact of climate change on mangroves, resulting from the 1992 Rio Conference (UNEP-UNESCO 1993). Considering only the responses related to geographical expansion and changes in area cover, in the first decade (1991-2001) of the studied period, there were only 16 published papers on the subject. In the following decade (2002-2012), there was an increase of over 3-times, with the publication of 58 studies. More recently, the subject raised attention worldwide and at least 13 papers appeared in 2013 alone. Up until now, 12 papers have appeared in 2014-15, on the specific aspect of the mangrove response to climate change. Concerning the country of origin of each paper, the United States, Brazil and Australia have the largest number of published studies, with 34%, 16% and 15% of papers, respectively. The Asian continent, despite not having any individual country with a large number of publications, has, as a whole, a large importance when viewed as, with 14% of articles distributed in eight countries. The other studies, about 20% of the total, were global reviews or multinational publications.

All these countries have significant mangrove areas, thus it is understandable that they carry out the greatest amount of studies. In the case of the United States and Asia, most of the mangroves are located in large populated areas frequently affected

by severe storms and hurricanes, extreme climatic events, which are more likely to be affected by global climate change, and, therefore, with potential significant impacts on mangroves. Furthermore, some of these regions are island regions or low-lying peninsulas and deltas, which are much more susceptible to sea level rise, which makes the preservation and understanding of mangroves an even more urgent matter.

In the last 50 years, between 30% and 50% of the mangrove forests have disappeared, this loss is continuing and in some places, it is even accelerating. The rate of coastal ecosystems annual loss is 4-times the rate of tropical forest loss (Copertino 2011). Mangroves of the Pacific islands are the most at risk due to erosion and deforestation. Mangroves along mainland Asia also witness severe pressure from their fast conversion into urban and agricultural development. In this scenario, climate change apart from promoting specific pressure on mangroves could maximize the impacts from other anthropogenic drivers.

Some recent reviews on the environmental pressures on mangroves due to climate change suggest that important threats to mangroves are mostly due to changes in salinity, wave regime, and the quantity and quality of the sediment loading (Giri et al. 2011), which may be further enhanced by increasing the frequency of extreme climatic events. For example, based on the IPCC maximum sea level rise scenario Gilman et al. (2006, 2007) predicted an up to 13% loss for Pacific island mangroves by the year 2100. Similarly, Alongi (2008) arrives at a global loss rate of mangroves related to climate change of about 10-15%.

Laurence et al. (2011) in a study about the most fragile ecosystems in Australia, pointed out that mangroves are a vulnerable ecosystem due to their narrow environmental tolerances, their geographically restricted distribution, their proximity to dense human populations in coastal zones, their patchy and fragmented location in the

country and their reliance on a few key framework species. The authors believe that the increase in storm intensity and the likelihood of the mangroves being squeezed between human land-uses or topography on the landward side, and rising sea levels on the seaward side, is the major threat to these forests. Other threats indirectly related to climate change are changes in salinity and hydrology. Mangroves that cannot keep up with rising sea level or do not have space to migrate inland will suffer the risk of drowning (Gilman et al. 2008).

Some researchers however, have found that not all mangroves will respond negatively to a climate change scenario. Recent studies showed that in many locations mangrove vegetation are expanding their poleward limits. Cavanaugh et al. (2014) observed that mangroves are expanding northward, from their original latitudinal limit along the east coast of the USA, and further suggested that this expansion is associated with the decrease in the frequency of discrete cold events ( $-4^{\circ}\text{C}$ ) due to recent global warming. Along this part of the North American coast, the spatial extension of mangrove forests has doubled, relative to the area recorded during the 1980's. These events would freeze and kill mangrove vegetation that crossed the poleward limits during the warmer periods of the year. However, these events are becoming less frequent and, consequently, mangroves are able to expand beyond their common territory. Studies in the Gulf coast in Louisiana in the USA also showed a mangrove expansion northwards with *Avicennia germinans* colonizing areas previously occupied by salt marshes, following two decades of warmer winters (Perry and Mendelssohn 2009).

In the Florida Keys, Stevens et al. (2006) showed that, mangroves are expanding since the last harsh winter and occupying places where salt marshes previously existed. Several other studies showed that, due to sea level rise, the mangroves have started to replace the original inland vegetation in several islands along the

Florida coast. In Sugarloaf Key, for example, the pine tree vegetation declined from an initial 88 ha before 1935, to 30 ha by 1991, partially replaced by the white mangrove *A. germinans*. The pine tree mortality occurred in low elevation areas, and probably resulted from both groundwater and soil water salinity increase. Higher water salinity appeared in areas of rapid pine forest reduction and the pines sampled in these areas exhibited higher physiological stress (Meeder et al. 1993, Ross et al. 1991, 2009). In the Atlantic coast of Florida, in the Everglades, *Rhizophora mangle* L. has expanded landward more than 1,000 meters into marshlands previously occupied by *Cladium* and *Eleocharis* (Ross et al. 2000), possibly in response to higher sea levels, changing groundwater levels, and shifting fire regimes (Smith et al. 2013). On the other hand, under carbonate settings with little or no allochthonous sediment input, such as on small, low-lying islands of the Caribbean and the Keys region, with little land area and an unsuitable land surface elevation gradient, mangroves cannot cope with sea level rise (Ellison and Stoddart 1991).

McKee et al. (2004) showed that an extensive dieback of salt marsh occurred throughout the Mississippi River deltaic plain in the year 2000. According to these authors, the phenomena affected more than 100,000 ha, with 43,000 ha severely damaged. Parts of these areas were colonized by mangrove vegetation, mostly *A. germinans*. Doyle et al. (2010) used mathematical modeling to predict how sea level change would affect the coast of the Gulf of Mexico and found that mangrove forests in the region showed a scenario of large expansion landward. This would result in a shift in the proportion of forest habitats with a loss of nearly 39,728 ha of freshwater forest and a gain of 21,784 ha of mangroves along the eastern Gulf States and a loss of 186,863 ha of freshwater forest but a small gain of 1,050 ha of mangroves in the western Gulf States.

Similar landward expansion occurred at Magdalena Bay, Baja California, on the Pacific

coast of Mexico. López-Medellín et al. (2011) reported a 20% increase in mangrove extent through landward migration into halophytic shrub land, associated with sea level rise, and particularly pronounced during El Niño seasons. The effects of strengthening of the El Niño, suggested by some global climate models (IPCC 2013) could accelerate mangrove expansion, as suggested by studies in this and other areas.

Another study from Baja California Sur, also reported an increase in mangrove area associated with sea level rise. Hak et al. (2008) found an increase of mangrove area of 7,575 ha between the years of 1986 and 2001. About 80% of the new mangrove area was colonized by *A. germinans*, occupying 6,056 ha and most of this increase occurred in the Magdalena Bay region.

In the southern limit of mangroves along the Western Pacific Ocean in Peru, the cold and arid conditions hinder mangrove expansion south of a small stand of mangrove vegetation in the Piura River Estuary (Clüsener and Breckle 1987). Mangroves in this estuary have expanded to 38 ha in the north arm and 9 ha in the south arm of the estuary, lining 9.5 km of shoreline and is the southernmost confirmed mangroves on the west coast of South America (Saintilan et al. 2014), however, similar to other areas, such as the South Atlantic latitudinal limit, evidence is still scarce to support poleward expansion due to global climate change.

Studies carried on in Australia and other Pacific countries have shown an increase in mangrove areas due to the influence of climate change on key mangrove growth controlling parameters. Eslami-Andargoli et al. (2009) reported landward mangrove expansion over salt marsh areas in Moreton Bay, between 1972 and 2004. They also found a significant relationship between rainfall patterns and the rate of mangrove expansion. According to these authors, mangroves showed a larger expansion in area during the rainy years between 1972 and 1990 than during the drier years



from 1990 and 2004. The higher supply of fluvial sediments, nutrients, lower exposure to sulphates and reduced salinity could be responsible for this larger expansion in wetter years.

A study by Williamson and Boggs (2011) in the Kakadu National Park, North Australia, found that, despite the damage caused by a cyclone in the study area, all mangrove swamps showed a landward growth over a 30-year period. This expansion rate was higher in swamps that have undergone hydrological changes due to engineering works but also occurred in other locations, without direct anthropogenic influence. Engineering works, such as dams, wave breakers and other coastal interventions are capable of maximizing the effects of climate change on mangroves (Lacerda et al. 2007, 2013).

A study conducted by Wilton (2002) in nine different locations in Australia revealed that, in almost all of the studied sites, the expansion of mangroves occurred at the expense of some other type of vegetation. From the 1940s to the 1990s, only 42% of the original area of salt marsh in that region remained, whereas mangroves replaced 58% of the existing salt marsh area, in 1990.

In New Zealand, a study conducted at the Firth of Thames by Lovelock et al. (2010) showed an accretion of mangrove forest of 1 km seaward over 50 years (an average of  $20 \text{ m y}^{-1}$ ). There were two major periods of mangrove expansion, one in 1978-81 and another in 1991-95. Both periods coincided with periods of sustained El Niño activity, an atmospheric phenomenon highly influenced by global climate change. Another study from Lovelock et al. (2007) showed that, in two other estuaries in New Zealand, fertilization and high sedimentation rate, probably induced by stronger El Niño, favored mangrove area increase.

Stokes et al. (2010) carried out a study in two embayments of Tauranga Harbour in New Zealand and found that spreading mangroves had become a coastal management issue even under

a temperate climate environment. The authors found that since the 1960s, mangrove habitats within both embayments have increased their intertidal coverage by around 15 ha and that local residents are currently clearing the seedlings. However, survival rates of up to 80% suggest that in the absence of human intervention, continued expansion of mangrove forests would be likely.

Asia is the continent with the largest mangrove area in the world and it is also where the mangrove forest are more diverse (FAO 2007), but lack of data and extensive clearing could hamper the studies on this region. In a review on mangrove expansion beyond their poleward limits, Saintilan et al. (2014) reported that historical data in Japan, for example, are insufficient to confirm mangrove expansion. Saintilan et al. (2014) also noted that the delimitation of mangrove limits in China and Taiwan are complicated due to extensive clearing. However, in the Zhanjiang Mangrove National Nature Reserve on the Leizhou Peninsula of Guangdong Province, China, one of the few locations where mangrove and salt marshes co-exist in near natural state, mangroves within this reserve have expanded fourfold, including encroachment on salt marsh area.

A study done in the Philippines showed that, between 1990 and 2010, there was a decrease of 28,172 ha of mangrove forest, about 10% of the mangroves in the country, with the driving force behind this decrease in several regions being the expansion of aquaculture and mangrove wood extraction. However, the largest loss of mangroves occurred due a typhoon in 1990; however, his area showed signs of recuperation after the occurrence (Long et al. 2014). Human induced land-use change were also indicated as the major drivers of mangrove area decrease in Southeast Asia and Vietnam (Nguyen 2014) mainly due to clearing for areas for urban and rural expansion and for aquaculture, this is also true for other Asian countries like Myanmar and India (Rao et al. 2013, Rahu et al. 2012). Therefore,

it is very difficult to monitor mangrove area changes in the Asian continent without the interference of direct human drivers.

Notwithstanding, at the Sundarbans, one of the largest mangrove forests in the world located along the Indian and Bangladesh coast, mangroves are disappearing at fast rates due to the drowning of the deltaic island, over the past three decades (Shearman et al. 2013). Subsidence, a decreasing in sediment transport from the Ganges and other rivers to the sea due to damming, and rising sea level, resulted in a dramatic decline in mangroves growing on islands, particularly in the central and eastern sectors of the Sundarbans (Rahu et al. 2012). In other river deltas, sea level rise, storms, and cyclones enhanced subsidence and declines in sediment supply, resulting in a landward migration of mangroves but with a net contraction (Alongi 2015).

Africa is where 20% of the world's mangroves are located, according to Taylor et al. (2003). Mangrove ecosystems of eastern Africa are well studied with 265 published papers between 1950 and 2000, 92% of those are centered in Kenya. This information is often not disseminated and the major reason is that the findings are generally confined to their countries of origin due to the numerous different national languages in the region. Overall, mangroves in almost every country in East Africa are decreasing due to human activities such as logging for fuel and house building, urban expansion, salt and shrimp production.

Di Nitto et al. (2014) simulated landward migration of mangroves in the Gazi Bay, Kenya, until the year 2100. The produced scenario showed that mangroves under low to medium sea level rise could shift without significant losses. However, under a maximum sea level rise scenario further landward migration would be obstructed by a strong increase of the topographical gradient.

South Africa is the southernmost area in Africa and 40% of its estuaries have lost their mangroves forests since 1982, resulting in only 24 estuaries

with pristine mangroves today (Adams et al. 2004, Rajkaran et al. 2009). Their fragmented distribution pattern makes South African mangroves highly vulnerable to extreme events. According to Quisthoudt et al. (2013) one sea storm, causing estuarine mouth closure and prolonged inundation of intertidal areas could cause the loss of mangroves in a whole estuary, turning them particularly vulnerable to the increase in the frequency and intensity of extreme climatic events associated with climate change.

Notwithstanding the general decrease in mangrove areas due to direct human pressure, reports from South Africa have also shown an increase of mangrove area in protected areas (Taylor et al. 2003). Saintilan et al. (2014), showed that mangrove area in the country has increased in 40%, within the past three decades with the largest expansion occurring in the Umhlathuze estuary with an increase from 197 ha to 489 ha over new sedimentary deltaic areas in that estuary (Bedin 2001, Ward and Steinke 1982).

Brazil is home to the second largest mangrove area in the world and Brazilian mangroves are under increasing pressure from a combination of human activities such as increasing coastal development, agricultural run-off, pollution and intensive aquaculture (Santos et al. 2014, Spalding et al. 2010). However, contrary to most countries harboring mangroves, in Brazil this ecosystem is considered as permanent preservation forests by the environmental legislation.

The Amazon Region has one of the largest macrotidal mangrove coasts of the world, with almost 7,600 km<sup>2</sup> (Souza Filho 2005). Within this region at Bragança, severe coastal erosion induced a shoreline retreat of 32 km<sup>2</sup> between the years of 1972 and 1998 and resulted in a mangrove area loss of 12 km<sup>2</sup> (Souza Filho and Paradella 2003). According to the study, the causes of the dramatic changes in the Bragança coastal plain are speculations due to the lack of historical series on



wind, waves, and tidal currents data, but may be associated with increasing ocean forcing on the continental shelf along this section of the Brazilian coast (Dias et al. 2013).

Another study done in the same region showed that despite measured reduction in mangrove coverage along the coastline, there was an active growth of mangroves in topographically higher plains previously occupied by grasses and herbs. This upland vegetation occupied an area of 8.8 km<sup>2</sup> in 1972 and reduced its cover to 5.6 km<sup>2</sup> in 1997, being substituted by mangroves. A linear extrapolation of the process showed that the total area of high plain vegetation would be covered by mangrove in 2035 (Rubén et al. 2002).

Object-based approaches and SAR data for mapping and detecting changes in the extent of mangroves along the coastline southeast of the Amazon mouth, known as the Amazon Macrotidal Mangrove Coast (AMMC), showed that over a 12 year period (1996-2008), the total area of mangroves increased by 718.6 km<sup>2</sup> from 6,705 km<sup>2</sup> to 7,423.60 km<sup>2</sup>, with 1,931 km<sup>2</sup> of expansion and 1,213 km<sup>2</sup> of erosion noted and 5,493 km<sup>2</sup> remaining unchanged in extent. The observed expansion of large mangrove areas in the AMCC seems typical of this region (Nascimento Jr et al. 2013).

In one of the few other large continuous extensions of mangroves in the world, the Gulf of Papua in Papua New Guinea, Shearman (2010) showed a reduction in the mangrove area from 1973 to 2002. In the Sundarbans in Bangladesh and India another region of large mangrove extension, the total forest areas have remained unaltered during the same period (Giri et al. 2007, 2008). However, both studies restricted their mapping to the seaward fringe, failing to account for any expansion landward, which seems typical of these large stands of mangroves responding to sea level rise, as shown for the AMCC in Brazil.

Studies carried out on the northeastern coast of Brazil, showed that several areas of mangrove

forests located in estuaries are increasing. Maia et al. (2006) compared, by means of remote sensing, the present extension of mangrove forests with maps published previously that used radar materials and aerial photographs, in 1978 (Herz 1991), and showed an increase in mangrove area from 444 km<sup>2</sup> to 610 km<sup>2</sup>, approximately 37% during a period of 25 years, although the different methodology and instrumentation probably overestimated this expansion.

A study done in the Jaguaribe River, the largest river in the state of Ceará, showed an increase of 24.15 ha in the area of islands within the estuary, between the years 1992 and 2003, by means of similar satellite image analysis of the entire period. These islands are rapidly being colonized at present, by mangrove vegetation (Fig. 1). The increased rate of sedimentation in the estuary caused by land-use drivers is aggravated by the decrease in river flow caused by damming but also by the decrease in rainfall over the basin caused by global climate change (Godoy and Lacerda 2014). Furthermore, the residence time of water and materials in the estuary is increasing due to the increasing oceanic forcing in the continental shelf, because of excess heat accumulating in the South Atlantic due to global warming (Dias et al. 2013, Lacerda et al., 2013).

A study conducted by Lacerda et al. (2007) on the mangrove expansion at the Pacotí River estuary, in the metropolitan region of Fortaleza, state of Ceará, showed that, in addition to colonizing old salt pits, mangroves also grew on recently enlarged estuarine islands and beaches. According to the authors, between 1958 and 1999, six new islands emerged in the estuary. These new areas were quickly occupied and secured by mangrove trees, which increased the areal coverage from 71 ha in 1958 to 142 ha in 1999. After that period, mangrove areas continued to expand, reaching 144 ha in 2004. In both cases, it is difficult to differentiate impacts caused by local human activities and global environmental changes, since the estuary responds



**Figure 1** - Mangrove growth in an island located in the Jaguaribe River, sand beach in 2009 (Top) and the same beach in 2010, now colonized by established mangroves seedlings (Bottom).

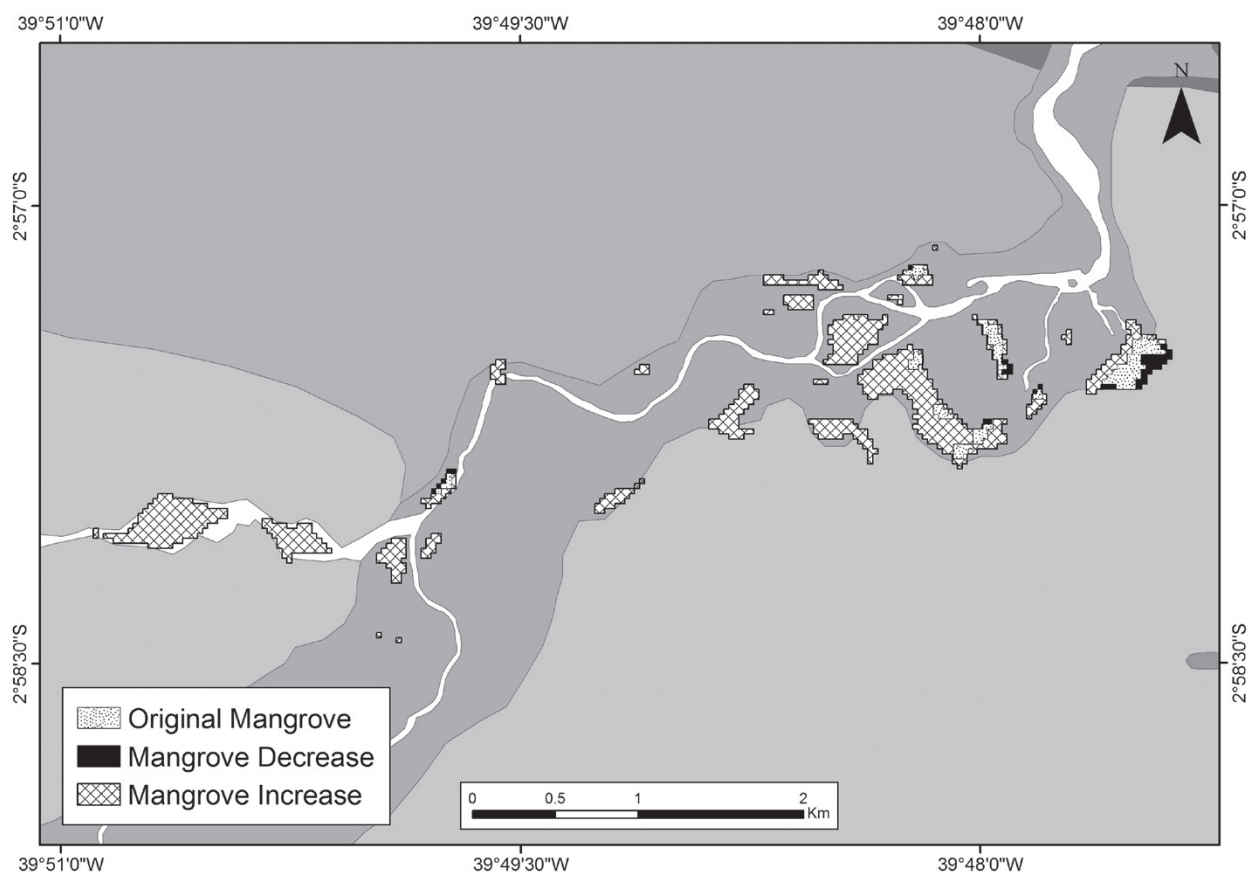
to alterations occurring throughout its watershed, in particular the damming of rivers. River damming is a very important feature in the state of Ceará, this region is located in the semi-arid portion of Brazil and, due to this climatic characteristic, and most of the rivers have some sort of water reservoir for human consumption. According to the company

responsible for monitoring the water level of the dams, there are 149 monitored reservoirs throughout the region (COGERH 2015).

Studies carried out in twelve estuaries in the state of Ceará showed that, of all studied areas, nine are showing an increase in mangrove forest area; however, climate change alone is not enough

to explain these changes. One of the studied areas was the Aracatimirim River estuary (Fig. 2), this estuary showed an increase of more than 400% in mangrove area between 1993 and 2008. Most of the newly formed mangroves areas are in newly formed islands and sand bars. The trapping of sediments inside the estuarine region is due to the low freshwater output, caused by damming, and to decreasing annual rainfall and the increasing seawater forcing, both associated with global climate change.

These results found in Brazil are consistent with the reports made by the Brazilian Panel on Climate Change (PBMC 2013) where it was stated that alterations in water volume and sediment transport caused by significant changes in the watershed such as damming could cause different impacts, particularly mangrove area expansion, which may be further aggravated by global climate change. Notwithstanding, no significant changes in mangrove expansion poleward was evidenced in the southern latitudinal limit of mangroves in the South



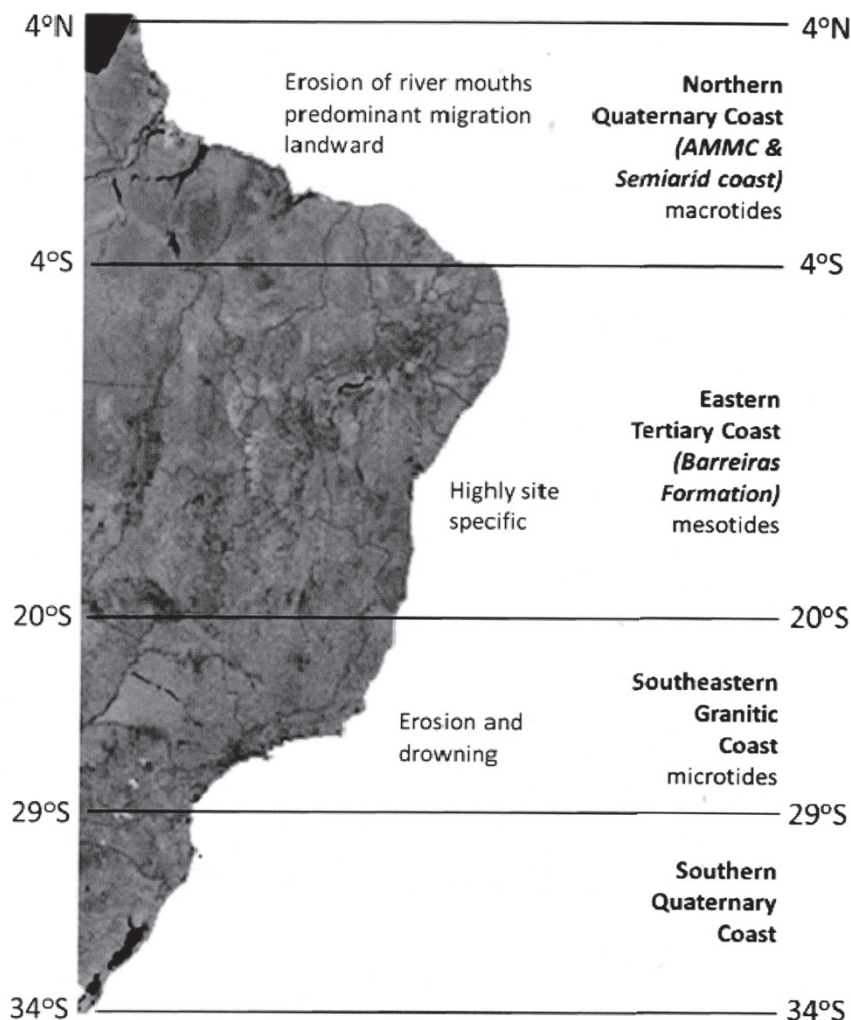
**Figure 2** - Mapping of the Aracatimirim Estuary between the years 1993 and 2008 showing the mangrove spreading landward along the estuary.

Atlantic at Laguna, in the state of Santa Catarina. However, it is expected that in response to global warming, these forest may expand southward, most by *Laguncularia racemosa*, presently limited by harsh climatic conditions in winter. This extension

southward may result from an increase in air and ocean surface temperatures, a reduction in the frequency of frost events, stronger influence of the Brazil Current and a weakening of the Falkland Current (Soares et al. 2012).

Based on the results available up until now, Figure 3 summarizes climate change impacts on Brazil's mangrove forests relative to area cover and distribution. Along the Northern Quaternary Coast, including the Amazon Macrotidal Mangrove Coast (AMMC) and the Northeastern semiarid coast, mangroves are mostly expanding landward,

responding to sea-level rise and saline intrusion. At the Northeastern semiarid coast, reduced annual rainfall and damming of rivers enhance saline intrusion and accelerate mangrove expansion and landward migration. However, erosion of mangroves at the mouth of rivers and in subsiding deltaic island are locally counter balancing this trend.



**Figure 3** - A summary of identified mangrove responses to climate change along the Brazilian coast. Division and classification of the coast follow Lacerda et al. (2003) and Knoppers et al. (1999).

In contrast, along the Southeastern granitic coast, mangroves are disappearing faster due to being squeezed within the narrow coastal plains by sea-level rise and increasing frequency of extreme weather events, and further maximized by strong

human pressure. At the southern tip of this zone, mangrove forests may expand their latitudinal range as temperature and atmospheric CO<sub>2</sub> concentrations increase and the frequency of extreme cold events decrease, although as noted by Soares et al. (2012)



no evidence exists on this southward movement of the local mangroves. Along the Eastern Tertiary Coast, little, if any data exists on the response of mangroves to climate change in relation to their cover area and distribution. The extremely high diversity of habitats and morphological setting of this coast and the enormous pressure from anthropogenic drivers may result in different responses at the local level; therefore, a general tendency cannot be presently depicted.

### DISCUSSION

Worldwide mangroves have decreased by 35 to 86% depending on region, as a response to direct human pressure associated mainly with urban expansion and aquaculture (Duke et al. 2007). The major factor determining mangrove resilience to climate change-related sea level rise and warmer conditions are landward and poleward migration. Evidence of poleward migration suggests the upmost influence of the decrease in the frequency of extreme cold events. The further expansion and the survival of the ecosystem as a whole, however, are then mainly determined by local and regional factors. The local arid climate seems to be the case of the mangrove southern limit at the Pacific coast of South America, for example. Coastal topography and/or sediment accretion allowing the system as such to migrate landward and to maintain a suitable surface elevation is also involved in the poleward migration of mangroves. Consequently, coastal development, such as urban expansion and hard engineering coastal protection works, becomes even more important in this context.

Landward migration and change in area covered seems to be the major response of mangrove ecosystems to climate change, and depends on a number of other factors determining the environmental setting, including rainfall and temperature variability (Woodroffe 1992, Esmali-Andargoli et al. 2009, Godoy and Lacerda 2014). Geomorphology of the coastal plain and sedimentation rates keeping pace

with the rate of sea-level rise are key parameters controlling the magnitude of landward migration. In those environmental settings that have sufficient allochthonous sediment input and/or production and accumulation of organic matter and a suitable gradient of land surface elevation, sea level rise does not constitute a threat to mangroves. This generally holds true for the environmental settings that dominated by rivers, tides with abundant sediment supply and waves on prograding coasts (Woodroffe 1992). However, land uplift or subsidence, groundwater influx, vegetation and soil processes, and whether the coast is prograding or eroding also play important roles in determining the extent of the landward migration (Krauss et al. 2003, 2013, McKee et al. 2007, Lovelock et al. 2015).

Depending on the sediment input, mangroves accumulate peat or mud, which allows them to adjust to a rising sea level. The existing data show that sedimentation rates are frequently higher than current rates of sea-level rise facilitating migration landward (Alongi 2008, Lovelock et al. 2015). Locally, mangrove distribution and composition remain almost unaltered when the rates of sea level rise and sediment accumulation are almost similar. However, when the rate of sea level rise exceeds the rate of sediment accumulation, mangroves may be lost when the mean high tide becomes higher than the substrate elevation. This effect will be most vigorous in low-lying limestone islands with negligible allochthonous sediment input, as in some Caribbean islands (Ellison and Stodart 1991) and the deltas of a number of large tropical rivers where subsidence and disappearance of many deltaic islands are ongoing, as in the Sanderbans (Alongi 2015). Although Ellison and Stodart (1991) suggested that mangroves will be lost at rates of sea level rise  $>12$  cm per 100 years, much lower than any of the conservative modeling of sea level rise (IPCC 2013), evidence from past Holocene sea level rise due to post-glacial rebound has shown mangrove expansion under much higher sea level rising rates. Maul and Martin (1993) have



reported a relative sea level rise over the past 147 year of about ~30 cm in Key West, South Florida, equivalent to 23 cm per 100 years, almost twice the critical maximum threshold suggested by Ellison and Stoddart (1991), without any significant collapse.

In the past 80 million years, mangroves have survived sea level changes of 120 m depending on local settings and sediment budgets, therefore, the present sea level rise threatens mangroves in some few places but in other places it provides opportunities (Alongi 2008). This, in turn, will similarly result in adverse effects for the filter function and biogeochemical transformation of substances in some places, while it will improve conditions in others.

Contrary to the local, direct impacts on mangroves, impacts from global climate change are much more difficult to forecast and model and therefore, more difficult to minimize. Furthermore, generic environmental legislation is not applicable at this spatial and temporal scales and mangroves have been nearly absent from international global discussion, as well as regional panels on climate change. Besides, reliable results on this subject are still scarce, creating further difficulties in understanding the magnitude and consequences of the impacts. With respect to climate change, it is rather difficult to assess the indirect consequences for mangroves in terms of carbon and nutrient transformation and accumulation. Since mangroves represent a significant sink of carbon at the continent-ocean interface, their response to climate change may result in a negative or positive feedback to this change.

### CONCLUSIONS

The existing climate change scenarios point to temperature increase and a rise in sea level as the most important factors directly affecting the distribution of mangroves and strongly suggest an expansion of these forests (Field 1995, Alongi 2008). The accumulating observations lead us to

conclude that the mangroves cannot only endure within the new environmental conditions imposed by climate change but also, in some places, will flourish. Understanding how human activities and a changing climate are likely to interact and affect the delivery of services by these ecosystem, is of the utmost importance to the present decision-making process affecting the health of marine and coastal systems and their ability to sustain future generations. Regarding mangrove's response to global climate change, the studies analyzed in this review showed that although there are areas where mangroves will suffer due to environmental changes, mostly in oceanic islands and deltas of a number of large tropical rivers, and those coastal sites enclosed by steep slopes that are at risk of being drowned by the advancing sea, in most regions mangrove area will increase responding to increasing sea level, decreasing rainfall and saline intrusion. Under such environmental setting mangroves respond to changing conditions of waves and salinity by migrating to places farther inland, often at the expense of other plant species and their ability to take advantage of conditions of warmer winters by expanding their limits toward higher latitudes.

Human interventions involving resource exploitation, river basin processes and engineering works for shoreline protection, primarily aimed to adapt to global change, rather increase vulnerability of mangroves, diminishing mitigating options to address the adverse consequences of climate change. In fact adaptation options to enhance mangrove resistance and resilience to climate change suggests that it is the human-induced degradation of mangroves that needs to be addressed. Thus, regional monitoring to improve the understanding of mangroves' response, training and capacity building programs aimed towards the public and decision makers, towards an increased awareness of the value of mangrove ecosystem goods and services, will contribute to decreasing

the risk of mangrove loss related to climate change. The future of mangroves therefore, largely depends on the degree of human interventions and their interactions with climate-related changes.

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#### RESUMO

Manguezais funcionam como proteção natural para a linha da costa em casos de erosão e inundação, provendo importantes serviços ambientais. Devido à distribuição geográfica desse habitat na interface continente-oceano, é muito provável que sofra sérios impactos oriundos das mudanças climáticas, potencializados por atividades humanas na zona costeira. Esse trabalho revisa os resultados de estudos realizados nos últimos 25 anos sobre as respostas observadas dos manguezais às alterações ambientais causadas tanto por alterações climáticas. Foram levados em consideração 104 estudos de caso e de modelagem no mundo todo. A maioria desses estudos foi publicada depois do ano 2000 como um reflexo do relatório publicado pelo IPCC em 1997. Apesar de muitos estudos mostrarem uma diminuição global da área de manguezais no mundo devido à pressão antrópica direta, vários outros mostraram que, localmente, uma variedade de habitats de manguezal está se expandindo como uma resposta à mudança climática global. Em todo o mundo, uma migração em direção aos polos está ampliando os limites latitudinais de manguezais devido a invernos mais quentes, e a diminuição de eventos de

baixas temperaturas extremas, enquanto nas baixas planícies costeiras os manguezais estão migrando continente adentro devido ao aumento do nível do mar, como observado para o litoral nordeste brasileiro. Levando em consideração apenas as alterações climáticas globais, os manguezais irão exibir uma resposta positiva na maior parte de sua área de distribuição. Em algumas áreas, no entanto, como ilhas oceânicas baixas, como no oceano pacífico e no Caribe, e zonas costeiras restritas, como no litoral sudeste do Brasil, os manguezais mais provavelmente não sobreviverão.

**Palavras-chave:** clima, manguezal, limites, migração.

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