Mapping and assessment of protection of mangrove habitats in Brazil

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Abstract. This study has mapped mangrove habitat and assessed the protection of this environment across the coastal protected areas with the use of Landsat satellite images integrated with geographic information system (GIS) in the entire Brazilian coast. The results are important to satisfy a great number of needs, including scientific ones as well as planning and environmental managements in conservation efforts. A total of 1,071,083.74 hectares of mangrove forest was registered, with 86% of this value present in the macrotidal coast. Mangrove habitats have shown high level of protection with almost 83% of the area of mangrove cover located within protected areas if we consider three levels of governance – federal, state and municipality. 77% of protected mangroves are situated in protected areas of sustainable use. Focus on implementation efforts of these areas should be attempted as a way to ensure sustainable management of mangrove resources.

Key words: Protected areas, GIS, remote sensing, conservation

Resumo. Mapeamento e avaliação da proteção dos hábitats de manguezais no Brasil. Este estudo mapeou os hábitats de mangue e avaliou a proteção deste ambiente pelas áreas protegidas costeiras através do uso de imagens de satélite Landsat integrado com o sistema de informação geográfica (SIG) em todo o litoral brasileiro. Os resultados são importantes para satisfazer um grande número de necessidades, incluindo as científicas, bem como ações de planejamento e de gestão ambiental nos esforços de conservação. Um total de 1.071.083,74 de hectares de mangue foi registrado, com 86% deste valor presente na costa de macromarés. Os manguezais mostraram um nível elevado de proteção com aproximadamente 83% de sua cobertura vegetal localizada dentro de áreas protegidas, se consideramos as áreas instituídas pelos três entes do governo - federal, estadual e municipal. 77% dos manguezais sob proteção estão situadas em áreas protegidas das categorias de uso sustentável. Esforços na implementação destas áreas devem ser atentados, como forma de garantir uma gestão sustentável dos recursos provenientes dos manguezais.

Palavras chave: Áreas protegidas, SIG, sensoriamento remoto, conservação

Introduction

The accelerating destruction of natural habitats and consumption of natural resources by rapidly expanding human populations has caused huge impacts to ecosystems across the globe (Defeo *et al.* 2009). Many of these impacts are focused on world's coastlines that include a mosaic of mangrove forests, seagrass beds, sandy shores and coral reef ecosystems. Mangrove wetlands are dominant coastal ecosystems in subtropical and tropical regions throughout the world (Lee & Yeh 2009). Therefore, they are subjected to high level of anthropic pressure. More than 50% of the world's mangroves have been removed (World Resources Institute 1996), and in Asia and the Pacific region there is an estimated area loss of at least 1% per year (Ong 1995). In many countries mangroves are traditionally been used for timber, thatch, fuel food, medicines and a wide variety of other items (Lee & Yeh 2009). Commercial practices are being

increasingly adopted in developing nations due to strong pressure to increase wealth and living standards of people living in coastal areas (Alongi, 2002). Although in Brazil there are not concrete estimates, the occupation of the coastal zone has dramatically increased, exerting diverse and numerous stress on the coastal ecosystems (Leão & Dominguez 2000). Among the impacts that threaten the future of Brazilian mangrove, we can highlight the diversion of freshwater flows, deterioration of water quality caused by pollutants and nutrients as well as conversion into development activities such as agriculture, aquaculture (mainly shrimp farms), salt extraction and infrastructure, all of which contribute to the degradation and deforestation process.

Mangrove is an ecological term referring to a diverse aggregation of trees and shrubs that form the dominant plant communities in tidal saline wetlands along sheltered coasts (Lee & Yeh 2009). They occupy a harsh environment, being daily subject to tidal changes in temperature, water and salt exposure, and varying degrees of anoxia (Alongi, 2008). Ecosystem adaptations include aerial roots or pneumatophores, viviparous propagules, salt exclusion or salt excretion, wide environmental tolerances and ability to growth in different environments such as bays, beaches, sandbanks, river mouths and lagoons where seawater meets river waters or are directly exposed to the coastline (Schaefer-Novelli et al. 1990, Dahdouh-Guebas 2002, Lugo 2002, Nagelkerken et al. 2008, Polidoro et al. 2010).

The importance of mangroves has been well documented. They are recognized as repositories of marine biodiversity and provide a number of natural resources and ecosystems services that are vital to human survival and well-being (World Resources Institute 1996). The recent advances in estimating photosynthetic production indicating that, on an areal basis, mangroves are usually more productive than saltmarshes, seagrasses, macroalgae, coral reef algae, microphytobenthos, and phytoplankton (Alongi 2002). They also play an important role in stabilizing shorelines and in helping reduce the devastating impact of natural disasters such as tsunamis and hurricanes, as well as maintaining coastal water quality and functioning as nurseries and feeding areas for commercial and artisanal fishery species (Lægdsgaard & Johnson 2000, Benfield et al. 2005, Giri et al. 2007, Nagelkerken et al. 2008, Tse et al. 2008). In addition, recent studies have indicated the sensitivity of mangroves for tracking and interpreting global climate changes (Alongi 2008, Gilman et al. 2008). To provide

mapping and database of these keystone ecosystems for future monitoring of environmental changes is essential for efficient conservation actions.

Thus, remote sensing has played an important and effective function in the assessment and monitoring of mangrove forest cover dynamics (Giri et al. 2007). As it provides supplementary information quickly and efficiently, several studies have been developed using remote sensing around the world with mapping purposes (Benfield et al. 2005, Giri et al. 2007, Lee & Yeh 2009). According to these authors (op. cit.) the use of remotely sensed data offers many advantages including synoptic coverage, availability of low-cost or free satellite data, availability of historical satellite data, repeated coverage and the possibility to allow assessment of ground conditions over large and inaccessible areas, as well as recent advances in hardware and software. All these factors have helped to increase the usefulness of remotely sensed data.

Mangrove trees along the Brazilian coast include the following species: *Rhizophora mangle* L. (Rhizophoraceae), *R. harrisonii* Leechman (Rhizophoraceae), *R. racemosa* Meyer (Rhizophoraceae), *Avicennia schaueriana* Stapf & Leechman ex Moldenke (Acanthaceae), *A. germinans* (L.) Stearn (Acanthaceae), *Laguncularia racemosa* (L.) Gaertn. F. (Combretaceae) and *Conocarpus erectus* Linnaeus, 1753 (Combretaceae). The mangrove environments provide habitats for diversity of fauna, including threatened [i.e. *Trichechus manatus* Linnaeus, 1758 (Trichechidae) and *Lutjanus analis* (Cuvier, 1828) (Lutjanidae)], overexploited [i.e. *Cardisoma guanhumi* Latreille, 1828 (Gecarcinidae) and *Litopenaeus schmitti* (Burkenroad, 1936) (Penaeidae)] and migratory species [i.e. *Ixobrychus involucres* (Vieillot, 1823) (Ardeidae)]. The ecosystem occurs from the State of Amapá to Santa Catarina State in a coastline total of 7,367km and given these vast extension and biophysical diversity, distinct physical-environmental units can be differentiated, each with similar environmental and physiographic conditions and specific environmental processes (Schaefer-Novelli et al. 1990). It also shows economic importance for subsistence and livelihood in many coastal traditional communities, especially at the northern and northeastern Brazilian coast.

There have been several studies related to distribution, structure and variability of mangrove areas in Brazil which have generated a great amount of knowledge (Schaeffer-Novelli 1989, Schaeffer-Novelli et al. 1990, Schaeffer-Novelli & Cintrón-Molero 1999, Menezes et al. 2003, Bernini &

Rezende 2004, Silva *et al.* 2005, Soares & Schaeffer-Novelli 2005, Vedel *et al.* 2006, Benatti & Marcelli 2007, Krug *et al.* 2007, Menezes *et al.* 2008, Visnadi 2008, Cavalcanti *et al.* 2009, Cunha-Lignon *et al.* 2009a, Bernini & Rezende 2010) but current small scale mapping studies are restricted to Amazonian macrotidal zone (Souza-Filho 2005) or to Atlantic rainforest ecoregion's coastline (Fundação SOS Mata Atlantica & INPE 2009). Thus, there is a demand to assess the mangrove ecosystems at national levels to satisfy a great number of needs, including scientific ones as well as planning and environmental managements in conservation efforts. The overall objective of the present study was to map mangrove habitat and assess the protection of this environment across the coastal protected areas with the use of Landsat satellite images integrated with geographic information system (GIS).

Material and Methods

The coast of Brazil extends from tropical to subtropical areas (4°N–34°S) and can be divided into three sectors based on the tidal amplitude (Figure 1) as described in Knoppers *et al.* (1999): the macrotidal (tides higher than 4m) coast between the Orange River mouth and the Parnaíba River strandplain (4°N–3°S), the mesotidal (tidal amplitude from 2m to 4m) coast between the Parnaíba River mouth and south Bahia State (3–15°S), and the microtidal (tides lower than 2m) coast between south Bahia State and the Chuí (15–34°S). In all sectors the tidal regime is semi-diurnal. Although the most important mangrove forest in terms of area occurs in macrotidal coast, other zones in the mesotidal and the microtidal sectors are also relevant because of the presence of other biophysical mangrove units.
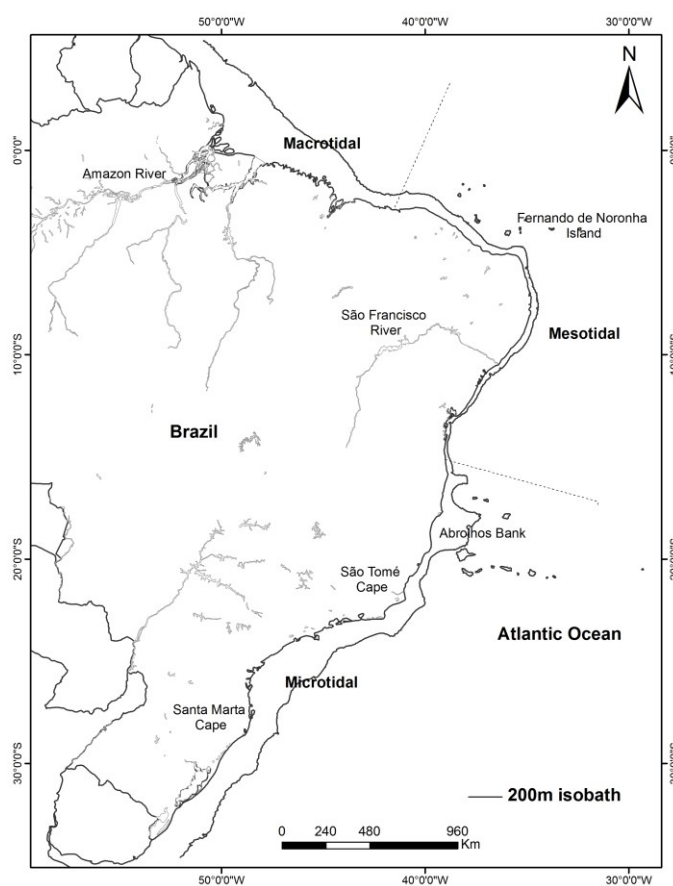

Figure 1. Map of the Brazil showing the macro, meso and microtidal coast.

To map the mangrove forest, Thematic Mapper TM/LANDSAT-5 satellite images, with pixel spacing of 30 m, were released by the Ministry of Environment and were used in this study. The images consisted of three (red), four (near-infrared), and five (medium-infrared) channels that cover the intervals 0.63-0.69 mm, 0.76-0.90 mm, and 1.55-1.75 mm, respectively. The images were geometrically rectified to the projection of geographic coordinate system, spheroid SAD69 and South America Datum 1969. To cover the entire Brazilian coast 72 scenes collected from 2007 to 2009 were used to obtain at least one cloud-free image of each area in the study region. Root mean square (RMS) errors were less than 30 m in agreement with mapping scale (1:100000). Band

composites 543 were used for mangrove forest detection through visual interpretation that was based on the following elements: color, texture, shape, size, context, geometry, and drainage system configuration. The mosaic of images was processed in ArcGIS 9.3, and two major classes were delineated: mangrove and non-mangrove. Although the salt flat constitutes the mangrove ecosystem, it was not considered in the present analysis because of doubts on the visual interpretation of this target. The mangrove forest polygons generated were quantified in terms of area and were analyzed as to their overlap with the location of coastal protected areas. The layers of protected areas were compiled from the data set of the Chico Mendes Institute for Biodiversity Conservation and the Brazilian Institute of Environment and Renewable Natural Resources.

The mangrove forest polygons were validated with basis in the literature, reports of researchers, available aerial photographs, and personal communications from staff of State Environmental Agencies.

Results

A total of 1,114,398.60 hectares of mangrove habitat was registered as depicted in Figure 2. If we considered the value obtained by global-scale mapping reference in World Mangrove Atlas (Spalding *et al.* 1997), the present result indicates that Brazil's mangrove correspond to roughly 7.1% of these ecosystems throughout the world. The macrotidal sector had 921,626.70 hectares that represented 83% of all mangrove forest in Brazil. In contrast, meso and microtidal sectors
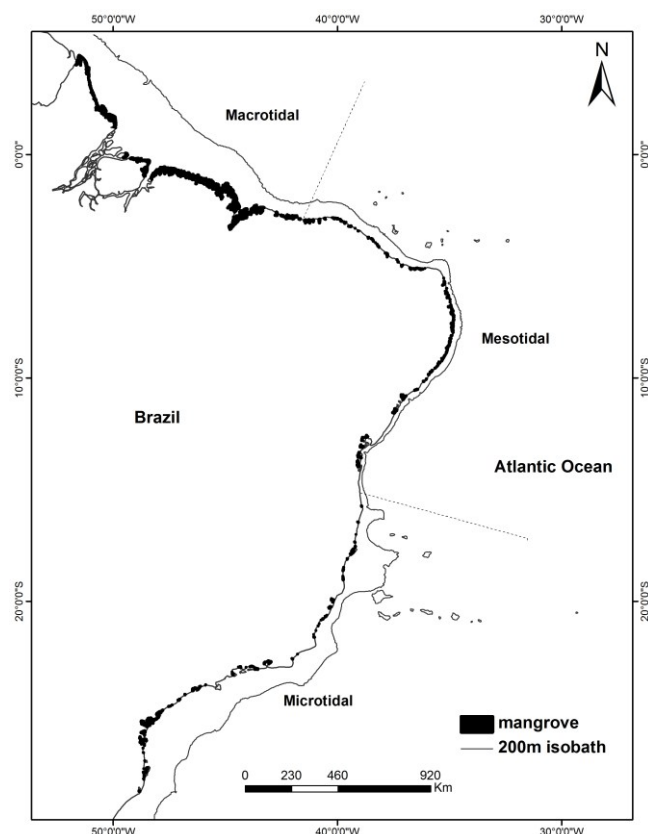

Figure 2. Brazilian mangrove forest extracted from satellite imagery.

had 117,709.63 and 75,062.27 hectares, respectively.

Figure 3 illustrates the mangrove map extracted from mosaic images in three sites along the Brazilian coast (macrotidal, mesotidal, and microtidal sectors). Important continuous patches of the mangrove habitat were mapped in Amapá State, at the region between Pará and Maranhão States, and at the region between São Paulo and Paraná State. However, mangrove habitat showed high fragmentation in the east coast. It was also possible

to identify extensive areas of shrimp farms in the northeastern coast, which threaten mangrove habitats.

Based upon the mapping of this study, mangrove ecosystems have shown a high level of protection, with more than 77% of the area of mangrove cover located within protected areas if three levels of governance, i.e., federal, state, and county, are considered. Table I shows the area of protected mangrove in each sector of coastal zone (macrotidal, mesotidal, and microtidal).
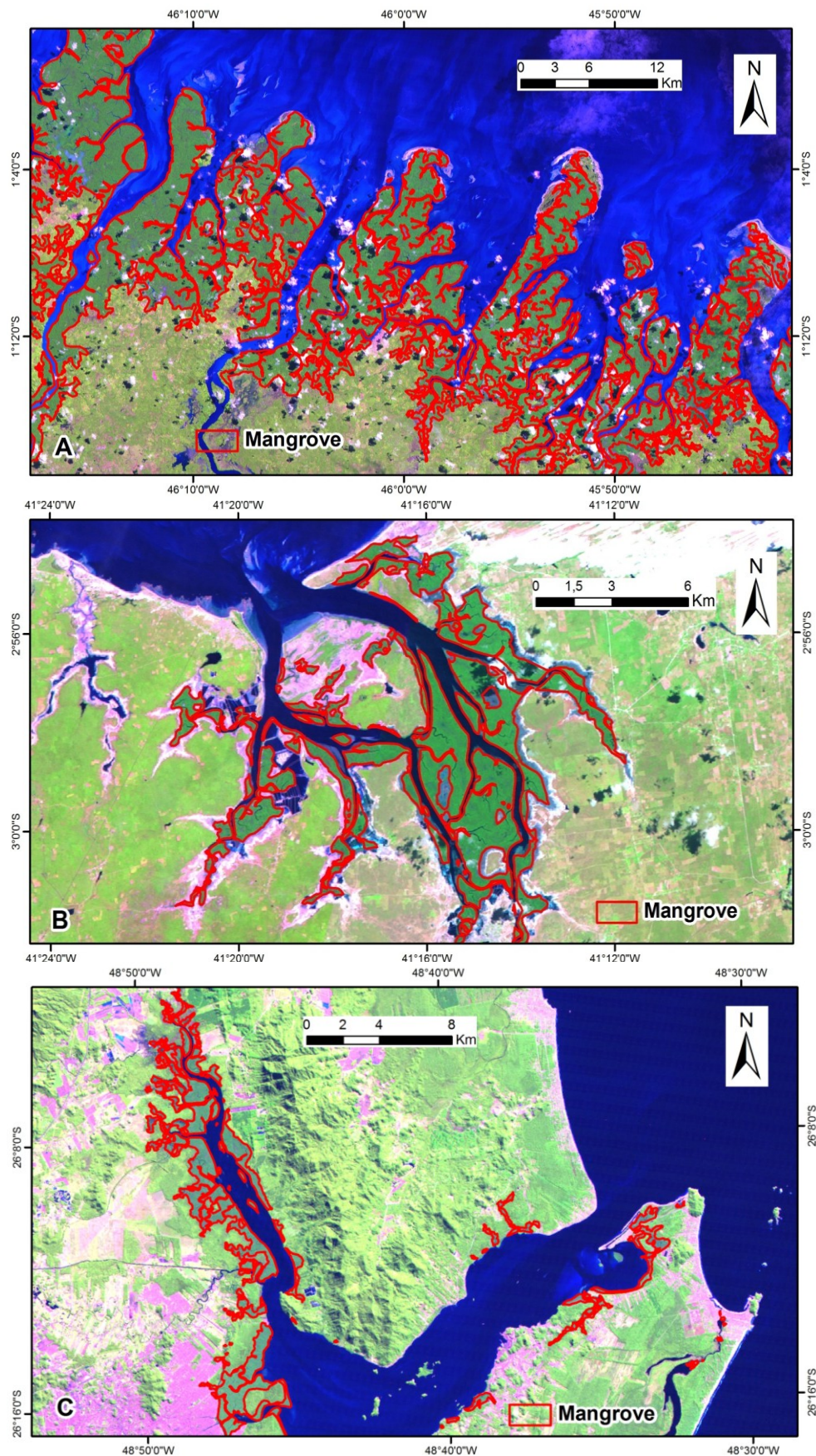
Figure 3. Mosaic of satellite images TM/LANDSAT-5 (4R5G3B) along the macro (A), meso (B) and microtidal (C) sectors of the Brazilian coast and mangrove polygons extracted from these images.

Table I: Mangrove in coastal protected areas along of each coastal sector in the Brazil; values are given in area and percentage.

Coastal sector	Mangrove in protected areas	
	Area (ha)	%
Macrotidal	810,892.96	87.98
Mesotidal	27,178.53	23.09
Microtidal	52,080.99	69.38

Our study registered 701,759.85 hectares of mangrove habitat on protected areas that focus on the sustainable use of natural resources (79% of protected mangroves). Most of the protection is provided mainly under the categories of Environmental Protection Area (APA) and Extractive Reserves (RESEX). When only those protected areas at the federal level are considered, the disparity between the protection provided by sustainable use and that provided by strict conservation protected areas is lower. In this case 425,530.57 hectares of protected mangrove forest were registered: 201,123.52 ha under strict protection and 224,407.05 ha under sustainable use. Table II shows the most important protected areas for mangrove ecosystems. The greatest mangrove protected area is present in the Environmental Protection Area of Reentrâncias Maranhenses (>200,000 hectares). The role of the Biological Reserve of Lago do Piratuba can also be highlighted, with more than 88,000 hectares of protected mangrove under strict conservation.

Discussion

Remote sensing technology offers an efficient means to uniformly observe and quantify an entire region without relying on sampling and extrapolation. While the identification of land-cover patterns is usually done on a medium or large spatial scale and does not require remote sensing data with high spatial resolution, sequential remote sensing with very high spatial resolution can be used to view mangrove vegetation structure and see whether it has been degraded (Dahdouh-Guebas 2002). This data set provided a coherent foundation that will serve to regional-scale mangrove science, monitoring, and management applications, but future mapping studies should be focused on the aspects above mentioned.

As the lack of long-term data constitutes one of the major problems in predicting mangrove responses to human impact (Alongi 2002), remote sensing and geographic information system–based research will become increasingly more useful in allowing the combination of past and present data in order to predict the future, although this is still a challenge (Dahdouh-Guebas 2002). Remote sensing has also shown the ability to differentiate natural from human-induced disturbances (Cunha-Lignon *et al*. 2009b). Thus, the continued development and use of remote sensing techniques into the future can produce reasonable prognosis of the threats, evaluate reforestation or restoration projects, determine accurate rate of loss, identify top-priority conservation sites, and help to raise the enforcement of laws and regulations. The values of mangrove area encountered in this study were similar to those registered in other estimates. In the previous estimate of the World Atlas of Mangrove, Brazil had mangrove area of about 1,340,000 hectares, representing 7.4% of the world's mangrove (Spalding *et al*. 1997). Estimates by the Food and Agriculture Organization of the United Nations (FAO 2007) indicated that Brazil had 1,012,376 hectares of mangrove area; this value was defined with basis in more reliable estimate with reference to the year 1991. A more recent quantitative estimate at the national level is clearly needed. The result showing the greatest mangrove habitat occurring in macrotidal coast was expected and can be explained by trends of the increase in above-ground biomass with decreasing latitude (Alongi 2002). The wide extension of coastal plain, warmer climate, many wide-mouthed estuaries, and large tidal ranges that penetrate inland for several kilometers promote the development of highest mangrove forest in the north coast of Brazil as observed by Schaeffer-Novelli *et al*. (1990).

According to the estimates in the study of Valiela *et al*. (2001), the present-day mangrove forest area is substantially smaller than the original area, with an average loss worldwide of 35%; on a continental basis, the losses can be larger in the Americas (estimated rate of loss is 3.6% per year).

In spite of superb examples of mangrove uses for tourist, recreational, educational and scientific research activities in Puerto Rico and Florida, the demand for the conversion of mangrove to urbanized areas and shrimp ponds is intensive and pervasive in many countries of the Latin American and Caribbean region (Lugo 2002). In Brazil, this fact deserves attention because shrimp pond construction has been commonly performed on mangrove forests and salt flats as observed in our mapping.

Table II: Main coastal protected areas with mangrove ecosystems in the Brazil; protected areas are arranged in order of area of mangrove contained.

Protected Area	Categories	Gover-nance	Coastal Sector	State	Geographical Coordinates of Centroids	Area of Mangrove (ha)
Environmental Protection Area of Reentrâncias Maranhenses	Sustainable use	State	macro tidal	Maranhão	44°51'50.1"W 1°37'2.8"S	200,314.90
Biological Reserve of Lago do Piratuba	Strict conservation	Federal	macro tidal	Amapá	50°14'19.2"W 1°31'17.1"N	88,598.51
National Park of Cabo Orange	Strict conservation	Federal	macro tidal	Amapá	51°11'55.8"W 3°39'6.5"N	50,905.97
Environmental Protection Area Archipelago of Marajó	Sustainable use	State	macro tidal	Pará	49°42'44.5"W 0°54'44.5"S	49,060.06
Environmental Protection Area of Baixada Maranhense	Sustainable use	State	macro tidal	Maranhão	44°57'56.5"W 2°56'25.5"S	41,233.65
Environmental Protection Area of Delta do Parnaíba	Sustainable use	State	meso tidal	Maranhão, Ceará and Piauí	41°51'54.2"W 2°49'19.7"S	35,250.06
Environmental Protection Area of Guaraqueçaba	Sustainable use	State	micro tidal	Paraná and São Paulo	48°26'7.1"W 25°15'45.9"S	13,543.01

Shrimp culture is, by a considerable margin, the greatest cause of mangrove loss worldwide (Valiela *et al*. 2001, Polidoro *et al*. 2010). Alongi (2002) carried out a consistent analysis of the threats to the future of mangrove ecosystems and classified them into three, i.e., high-, medium-, and low-level threats, based on the level of past and current impacts, and corroborated this statement. The author concluded that aquaculture is one of the major threats, being interlinked with both deforestation and overexploitation of fisheries resources (Table III). As pointed out by Lugo (2002), the gamble of converting mangrove forests and salt flats to shrimp ponds is that a sustainable resource with multiple values is converted to a system with a single output and a potentially high but possibly short-term economic payoff, with equally high management costs and risk of failure.

Although the accelerating rate of loss of mangrove forests may cause the disappearance of mangroves within the next 100 years (Duke *et al*. 2007), little is known on the effect of area loss on individual mangrove species or populations, and the threats seem to act differently along the estuarine zones. Mangroves species found primarily in the high intertidal and upstream zones, which often have specific freshwater requirements and patchy distributions, are the most threatened because they are often the first cleared for the development of aquaculture and agriculture (Polidoro *et al*. 2010).

The most recent estimated rate of habitat loss for Brazilian mangroves was published by FAO (2007), showing that at least 50,000 hectares of mangrove were cleared over the last 25 years. Furthermore, years of overexploitation and destruction of the habitat have resulted in a continuous decline in the stocks and a reduction in

the size of individuals of numerous crustaceans, including blue land crab [*Cardisoma guanhumi* Latreille, 1828 (Gecarcinidae)], swamp ghost crab [*Ucides cordatus* (Linnaeus, 1763) (Ucididae)], and blue crab [*Callinectes sapidus* Rathbun, 1896 (Portunidae)] (Wolff *et al.* 2000, Amaral & Jablonski 2005). This has direct economic consequences for human livelihoods that depend on the fisheries. Besides the habitat loss, several studies have also demonstrated that degraded ecosystems have become common in mangrove areas situated in the immediate vicinity of large cities (Harris & Santos 2000, Silva *et al.* 2001, Machado *et al.* 2002, Quevauviller *et al.* 2004, Hortellani *et al.* 2005).

Table III: Future threats to the world's mangrove forests. Source: Alongi, 2002.

High-level threats	Intermediate threats	Low-level threats
Deforestation	Alteration of hydrology	Oil pollution
Pond aquaculture	Global warming	Thermal pollution
Overexploitation of fish and shellfish	Eutrophication	Tourism
		Noise pollution

In Brazil, the Forest Code defines mangrove habitats as Areas of Permanent Preservation (APP) and provides restrictions on their uses. Total or partial extraction of natural vegetation is permitted only through the authorization of the relevant government agencies and when it is of public and social interest. Conversely, this legal instrument has not been enough to ensure the protection needed. One reason for this is that State Environmental Agencies determine, for each case, the level of land use restriction accepted. There is still no comprehensive licensing system of activities allowed in the mangrove areas and surroundings. Moreover, a recent study undertaken in an area under strong anthropogenic pressure (Guanabara Bay, Brazil) confirmed worse conservation status of the mangroves located outside the protected areas (Cavalcanti *et al.* 2009). It evaluated the effectiveness of the implementation of protected areas for mangrove forests, and the results showed significant differences regarding their main structural parameters within and outside of protected areas. Therefore, the role of protected areas is very important both to preserve the mangrove forest cover and to keep its structural and functional characteristic.

According to the Law of National System of Conservation Units, sanctioned in the year 2000, protected areas are defined as territorial spaces that together with their natural resources have been legally recognized by the Public Authority and have defined limits and conservation objectives and that are brought under a management regime to ensure adequate protection. These protected areas are divided into two categories: strict protection and sustainable use. The aim of protected areas of sustainable use is to promote the use of the ecosystem in ways that ensure the sustainability of renewable natural resources and ecological processes, whereas the strict protection areas allow only indirect use of natural resources such as for educational and scientific activities. Each category is further subdivided into many management categories with different ranks of protection. APAs, in general, are large areas with specific purposes to manage the process of human occupation, whereas RESEXs are established through the traditional population request with specific purpose to protect the livelihoods and cultures of these populations and their natural resources.

The high level of protection given to the mangrove habitat under protected areas of sustainable use should be viewed with caution in terms of adequate conservation. A bottom-up approach to participatory management is used in these categories, with the community, the government, and sector stakeholders working closely to create consensus-building which will be an important tool in threat mitigation. Some authors have questioned whether this approach can ensure the sustainable management of resources. As described by Edgard *et al.* (2008), the identification

of the sanctuary zones in the Galapagos Marine Reserve through of a bottom-up and stakeholder-driven process, following a series of face-to-face meetings and involving sector representatives, resulted in various biases such as having almost all conservation zones located along coasts with little fishery resources or with limited commercial diver access. Furthermore, the adequate conservation of the mangrove ecosystems must be attached by maintaining several other adjacent ecosystems such as sand dunes, sand bars, coral reefs, and mud flats, considering the biogeochemical complex interconnections among them.

Therefore, effective conservation needs to be provided by a network of coastal and marine protected areas to ensure the sustainable management of mangrove resources. While most of these areas are situated in the north coast, new protected areas should be established in other eco-regions, characterized by different morphologic forms and with specific environmental processes, such as in the northeastern and the eastern coasts. Furthermore, focus on implementation efforts in these areas should be attempted as a way of maintaining the biodiversity levels and the full array of services of this multifunctional ecosystem. Future studies need to be directed to long-term monitoring and mapping with higher-spatial-resolution images.

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