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GEOSCIENCES

Status of mangroves land use on the Brazilian Amazon coast from RapidEye imagery and GEOBIA approach

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Abstract: Given the ecological and socioeconomic importance of the mangroves of the Brazilian Amazon coast, RapidEye satellite images were analyzed to recognize mangrove forest and salt flat changes to different land use through human activities. Results show that mangroves are still very well preserved, with less than 1% of the total converted to other uses, primarily urban areas and roads. These human activities have been the principal causes of use in the mangrove forest, driven by local anthropogenic pressures resulting from human settlements in the transition zone between the mainland and tidal flats. In contrast, aquaculture, the principal driver of the loss of mangroves in other regions of South America and in Asian countries, plays only a secondary role in habitat conversion on the Amazon coast. However, these human activities demand more attention and policies need to be supported by Brazilian legislation.

Key words: Remote sensing, coastal environments, Salt flat, Brazil.

INTRODUCTION

The mangrove plays an essential role in the ecology of tropical coastal zones and has considerable socioeconomic importance for the local traditional communities (Carney et al. 2014, Giri et al. 2015). In Brazil, mangroves cover an extensive area of the coast, with a total of almost 9,900 km^2, approximately 73% of which is located on the Amazon coast (Diniz et al. 2019). The characteristics of this ecosystem vary considerably according to the tree species composition, and local climatic and edaphic conditions (Menezes et al. 2008). Mangrove forests may be either mixed, monospecific or dwarf, and may be associated to a greater or lesser degree with salt flats, which are hypersaline tidal flats (Ridd & Stieglitz 2002) found at the margins of the mangrove, and either lack vegetation altogether (Hadlich et al. 2010) or are covered with a herbaceous stratum, and are limited by the mean levels of the neap and spring tides (Schmidt et al. 2013). This salt flat zone, which is also known as the “apicum” plays an important ecological role, acting as a refuge, source of nutrients, and habitat for a range of animal species, in particular decapod crustaceans, contributing fundamentally to the maintenance of mangrove biodiversity (Schmidt et al. 2013).

Global statistics indicate that mangroves have been shrinking around the world as a consequence of human activities. In the the 1980s, the annual rate of loss of mangrove habitat was 1.04%, while in the 1990s, it was 0.72% (FAO 2007). At the beginning of this century, between 2000 and 2012, the most accurate estimate indicated a worldwide loss of mangrove habitat of 0.39% per annum. However, Southeast Asia was responsible for the majority of mangrove deforestation, with annual rates of 3.58–8.08%, with the highest rates being recorded in Indonesia, which was responsible for half of all the deforestation recorded globally in this ecosystem (Hamilton & Casey 2016). The loss of mangrove habitats is related primarily to the conversion of forest to aquaculture, in addition to urban and other infrastructure, and agriculture (Primavera et al. 2019).

In Brazil, while mangroves are legally protected under federal law (Brasil 2012), an area around 200 km^2 was lost between 1999 and 2018, which represents a reduction of 2% of the total area of Brazilian mangroves (Diniz et al. 2019). Aquaculture is the principal driver of the loss of mangrove habitats and salt flats in northeastern Brazil (Leão et al. 2018, Queiroz et al. 2013, Santos et al. 2014). Like the mangrove, salt flats suffer intense anthropogenic pressure in many parts of the world, related to the implantation of economic activities such as aquaculture (primarily shrimp farming) and the industrial production of salt (Giri et al. 2008, Oliveira & Freitas Filho 2017). A range of ecological and socioeconomic impacts have thus been recorded in mangroves and their associated salt flats (Schaeffer-Novelli et al. 2012).

Given the importance of mangroves, and increasing anthropogenic pressures on this ecosystem, remote sensing provides an important tool for the monitoring and assessment of the dynamics of land cover and use (Cárdenas et al. 2017, Cougo et al. 2015). Remote sensing is a fast and effective complement for the data collected during field surveys, given that many areas maybe inaccessible, in particular where substrates are difficult to traverse (Santos et al. 2014). A number of different satellite images and methods have been used to map the mangroves of the Amazon coast. These approaches include the visual interpretation of Landsat images (Freitas et al. 2018, Souza-Filho 2005), pixel-based classifications (Giri et al. 2011, Rodrigues & Souza-Filho 2011), and an object-oriented approach that has used synthetic aperture radar (SAR) images to map and detect changes (expansion and erosion) in mangroves (Krause 2010, Nascimento et al. 2013). On the other hand, few studies have mapped the anthropogenic conversion of mangrove habitats in northern Brazil, although Tenório et al. (2015) found that marine aquaculture has contributed to the conversion of 0.53 km^2 of the Amazonian mangroves, which represent 0.007% of the total area of this ecosystem. However, the extension of other types of land use, including that of the salt flats, remains unknown. With this in mind, the present study evaluated the status of the land use of mangroves and salt flats on the Brazilian Amazon coast through the analysis of high-resolution satellite images. The present study aims to identify, map, and quantify the mangrove forest and adjacent salt flat zones of the Brazilian Amazon coast, and identify the principal anthropogenic activities in this ecosystem. The results of this analysis provide important insights that should be used to support the decision-making processes adopted during the formulation of public policies for the systematic conservation of mangrove forests and the associated salt flats, thus contributing to the effective mitigation of different anthropogenic impacts.

MATERIALS AND METHODS

Study area

The study area comprises the mangrove belt located to the east of the mouth of the Amazon River, between Marajó Bay, in the state of Pará, and São José Bay, in the state of Maranhão (Fig. 1). This region has relatively homogeneous geomorphological features, suach as macrotide

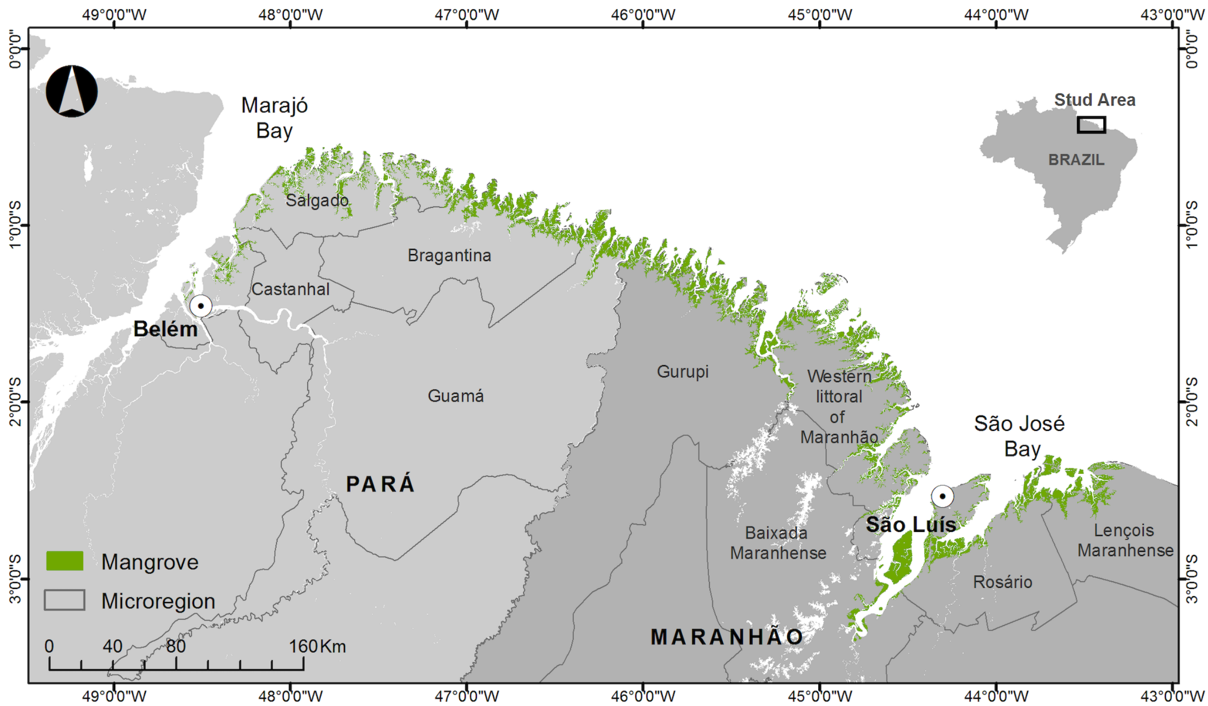


Figure 1. Study area formed by a continuous mangrove belt on the Brazilian Amazon coast, between Marajó Bay in Pará and São José Bay in Maranhão. Note the different environmental and socioeconomic microregions throughout the study area.

estuaries, tidal flats, mangroves and beaches, which supports similar patterns of resource use (Szlafsztein 2009). Most of the area of mangrove is subject to a macrotidal regime (Asp et al. 2018), with tidal amplitudes ranging from 4 m in Guajará Bay (Pará) to 7.5 m in São Marcos Bay, Maranhão (Nascimento et al. 2013). The relief of the region is low (up to 80 m a.s.l.), with an ample coastal plain, up to 70 km wide, lying adjacent to an extensive continental shelf (~200 km wide). The coastline is extremely irregular and crossed by a large number of different estuaries (Souza-Filho & El-Robrini 2000). The region's climate is hot and humid, with well-defined dry (July to December) and rainy (January to May) seasons, mean annual rainfall of between 2500 and 3000 mm, and a mean annual temperature of approximately 26ºC (Moraes et al. 2005).

Remote sensing dataset

The remote sensing data were obtained from the RapidEye satellite series, with an orthorectified spatial resolution of 5 m in the UTM projection, with five spectral bands (Planet 2018). A total of 86 scenes were used to map land cover and use in the study area (Supplementary Material - Table SI). These images are available in the database of the Brazilian Environment Ministry (MMA 2015). For each scene, an image was selected for analysis from between 2011 and 2015, based on the following criteria: (i) the availability of images from the most recent year, and ii) the least possible cloud cover. The final set of RapidEye images and their respective acquisition years are shown in Fig. S1.

Digital image processing

The principal step of the digital image processing and analysis for the mapping of the land cover and use in the Amazon coastal zone were the atmospheric correction to convert digital number (DN) of pixels of different scenes into ground reflectance (GR). Conversions from DN to GR were carried out in the Atmospheric Correction (ATCOR) module of the software PCI Geomatica 2016. The images were then orthorectified and mosaicked in the Ortho Engine module of the PCI Geomatica software. Later, the mosaic was segmented and classified through the geographic object-based image analysis (GEOBIA) approach (see Fig. S2). These steps included manual editing with visual interpretation and supervised classification, accuracy assessment, and data analysis (Souza-Filho et al. 2018).

Segmentation

The images were segmented using the multiresolution segmentation algorithm of the eCognition software. For this function, it was necessary to assign a weight to each associated image band and included: (i) scale; (ii) the shape parameter (brightness), and (iii) compactness parameters (Baatz & Schäpe 2000), based on the two different segmentation levels (Table SII). The first level is related to the fine segmentation, and contains small objects, such as areas of salt flat and anthropogenic use. The second level of segmentation is composed of larger objects that permitted the differentiation of the mangrove forest from the other types of land cover that were not mapped, such as water, vegetation on dry land, beaches, and dunes (Fig. 2). Based on segmentation levels 1 and 2, parameters were defined so that the larger objects included the boundaries of the mangrove forest, urban areas, and clouds.

Classification

The classification followed the decision tree approach, which establishes the order and sequence of the processing and stores all the elements or rules necessary to extract the classes at the object level (Table SIII). During the classification process, the objects generated at segmentation level 1 had spectral similarities with some classes of anthropogenic use. These classes were also represented by small objects to obtain a more accurate classification, manual editing was used to interpret visually the shape,

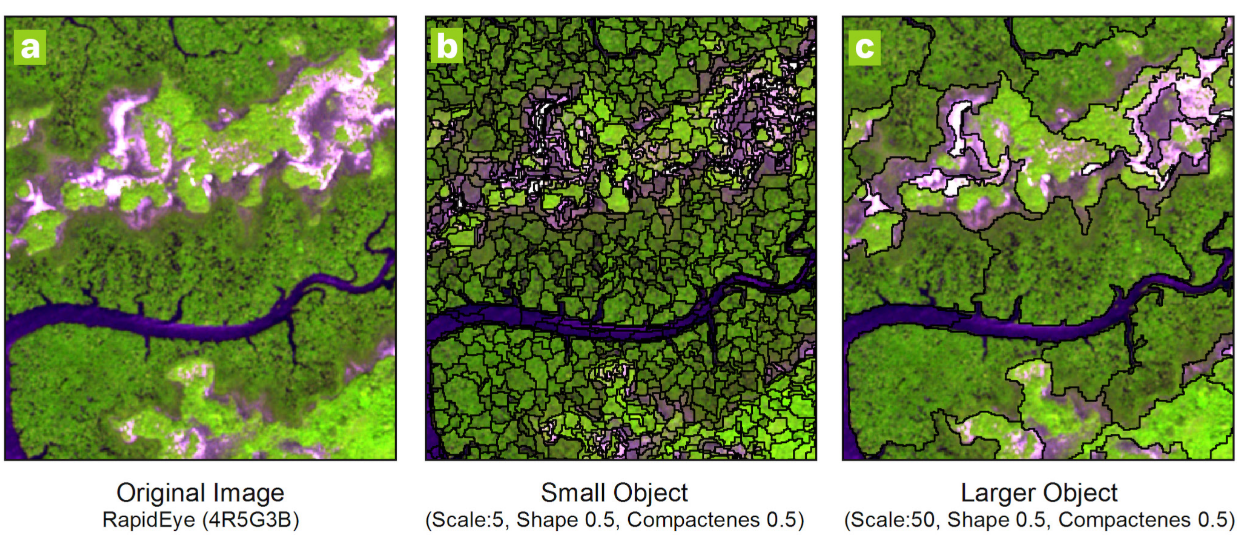


Figure 2. Segmentation levels of the RapidEye images. (a) RapidEye image (25/11/2014) adopted for processing. The R, G, B were set to band 4 (red-edge), band 5 (green), and band 3 (blue). Results of multi-resolution segmentation with scale parameters 5 (b) and 50 (c).

texture, hue/color, and spectral behavior of the units that make up the landscape (Souza-Filho et al. 2018). Essentially, this technique combines the advantages of the semiautomated generation and classification of fine-level objects with the benefits of visual interpretation (Lang et al. 2009). At the end of this process, 12 classes were recognized to represent the land cover and land use of the study area (Fig. 3), according Di Gregorio (2005).

A 2008 map of the mangrove was used to quantify the areas of forest under cloud cover (Nascimento et al. 2013). In this case, the cloud class was replaced by mangrove whenever this class was mapped in the reference map. Areas classified as urban, data from before 1973 (Nascimento et al. 2013) were overlaid

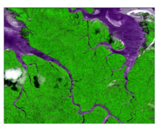
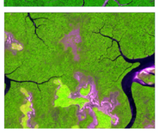
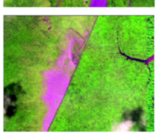
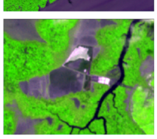
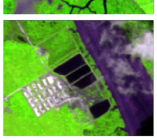
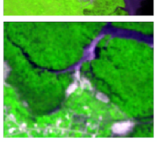
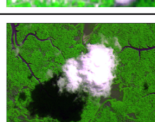
	Class	RapidEye (4R5G3B)	Description
Land cover classes	Mangrove forest		Area covered by mangrove forests.
	Salt flat		Sandy soil, devoid of vegetation or herbaceous vegetation (Schaeffer-Novelli et al. 2002). Transition zones found mostly between mangroves forests and adjacent dry upland areas (Hadlich et al. 2010, Ucha et al. 2008), also ocurring within mangrove forests (Hadlich et al. 2010, Schmidt et al. 2013), whose limits are set by the mean level of the spring tides.
Land use classes	Deforestation		Removal of the mangrove tree cover and predominance of exposed soil.
	Degradation		Area with impairment of wetland functions because of human activity (Plesnik et al. 2011). Area with low development of mangroves, compacted sediment, and low frequency of flooding by tidal waters (Fernandes et al. 2007).
	Road		Paved or unpaved road that crosses a certain territorial extent of mangrove, containing narrow adjacent areas of exposed soil.
	Urban area		Human settlement with high population density and infrastructure of built environment.
	Salt pond		Area inside mangrove or salt flat with shallow artificial ponds designed to extract salts from seawater through natural evaporation.
	Aquaculture		Area within mangroves or salt flats for fish and crustacean farming.
	Port		Near shore area with sufficient depth where vessels can anchor and load/unload cargo.
Other	Cloud		Cloud and cloud shadow.

Figure 3. Description of land cover and land use classes in study site.

with the areas classified as urban to determine mangrove cover. For the analysis of the different types of use of the mangrove forest and their associated salt flats, the study area was divided into 11 microregions (Fig. 1), based on the criteria defined by the Brazilian Institute of Geography and Statistics (IBGE 1990), according to the environmental and socioeconomic characteristics of the respective areas.

Validation

The accuracy of the classification was determined through the analysis of 2330 ground control points (GCPs) collected in a stratified random fashion in the ArcGIS software. These samples were interpreted visually according to the descriptions presented in Fig. 3. These data were then used to construct a confusion matrix (Congalton 1991, Foody 2002) and to estimate the producer, user, and overall accuracies, as well as the overall and per-class Kappa (Congalton & Green 2009) and Tau (Ma & Redmond 1995) values.

RESULTS

Accuracy assessment

The confusion matrix represents the quality of the classification of the land cover and use based on the correlation between the reference data and the classified data (Table I). The overall accuracy of the classification was 95.12%. Despite this, a degree of confusion existed among the areas of port, urban development, and roads. Confusion also existed between salt flats and salt evaporation ponds. The Kappa value was 0.92 and was confirmed by a Tau value of 0.94. The per-class Kappa was greater than 0.81 for all classes.

Table I. **Confusion matrix for land cover and land use classification. MF = mangrove forest; SF = salt flat.**

		Reference Data														
Class	**Code**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**Total**	**User Accuracy (%)**	**Commission Error (%)**
Mangrove forest	1	1176				2				23			6	1207	97	3
Deforestation (MF)	2		13											13	100	0
Degradation (MF)	3			7										7	100	0
Road (MF)	4	4	3		66		1							74	89	11
Urban area (MF)	5	3				106							7	116	91	9
Port (MF)	6				1	1	8							10	80	20
Salt pond (MF)	7							18						18	100	0
Aquiculture (MF)	8								11					11	100	0
Salt flat	9	20								556		6		582	86	14
Salt pond (SF)	10	1								8	52			61	85	15
Aquiculture (SF)	11	1									3	26		30	87	13
Cloud	12	20			1	1				1			164	187	88	12
Total		1225	16	7	68	110	9	18	11	588	55	32	177	2316	**Global accuracy 95.12**	
Producer Accuracy (%)		96	81	100	97	96	89	100	100	100	95	81	93		***Kappa*** **index 0.92**	
Omission Error (%)		4	19	0	3	4	11	0	0	0	5	19	7		***Tau*** **index 0.94**	

Analysis of the images and the types of land cover and use

The parameters selected for the segmentation permitted the adequate definition of the target areas in the images according to the type of land cover and use (Fig. 4). The aquaculture tanks in the mangrove presented a similar spectral response to those located in the salt flats, and the same result was obtained for the salt evaporation ponds (Fig. 4). For the visual interpretation, the best band composition was 4R5G3B, which permitted the identification and discrimination of salt flats and the different types of use, in the areas of both mangrove and salt flat.

The Brazilian Amazon coast presented an area of 7820.05 km^2 (Fig. 5a; Table II). Most of the study area is mangrove forest (7210.07 km^2 or 92%), while only 1% (66.85 km^2) presented

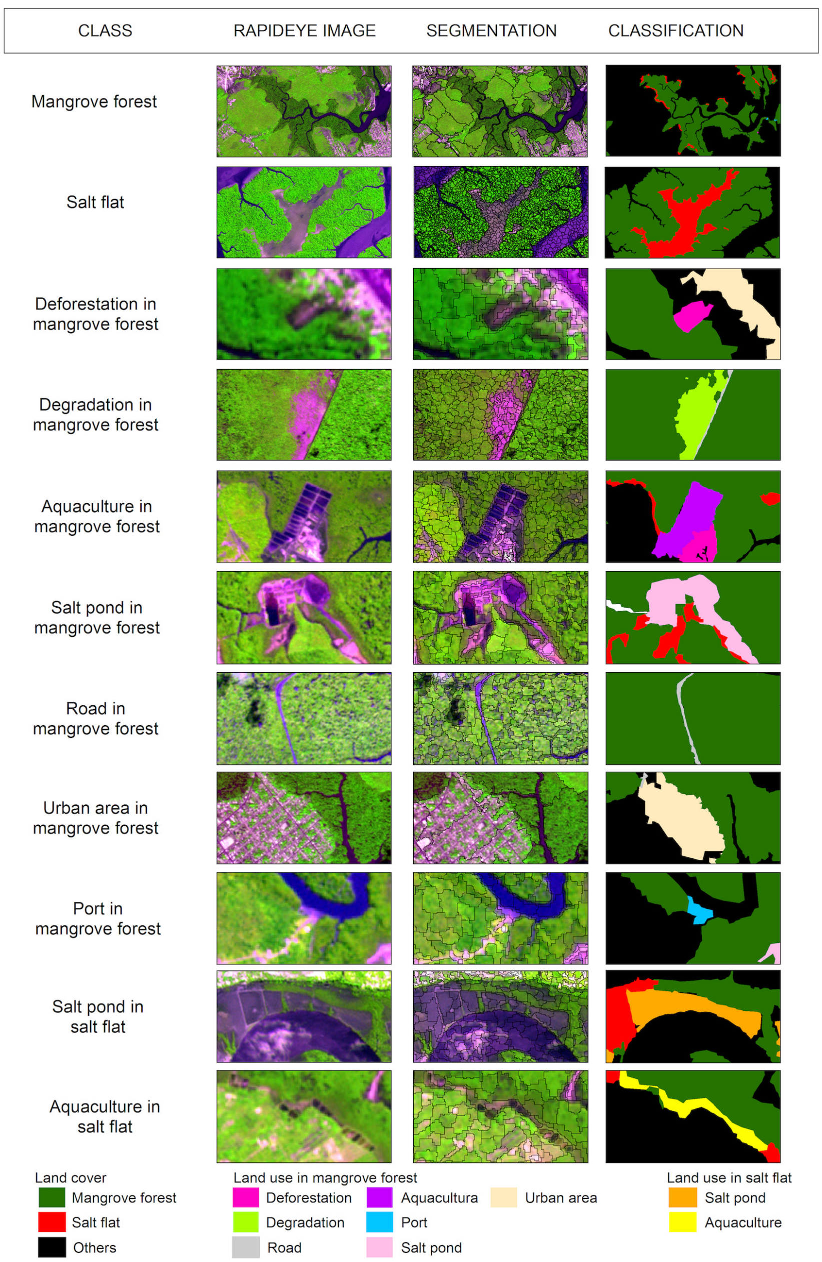


Figure 4. Different types of land cover and land use illustrated by the RapidEye images from between 2011 and 2015. Results of multi-resolution segmentation with different scale parameters and the classification of the different types of land cover and use.

some kind of land use. While most of this area (54.47 km^2) was located within the mangrove, it represented only 0.7% of the study area. Land use in the mangrove primarily involved urban development (88.2%), followed by roads (4.4%), degradation (3.1%), and deforestation, with 2.2% (Fig. 5b, c, d; Table II). In the salt flats, a total area of 12.38 km^2 was occupied by some type of land use, corresponding to 2.2% of the total area of salt flat (Fig. 5a; Table II). Salt production was the main activity responsible for the conversion of salt flats (97.3%), with only a small percentage of the area (2.7%) being used for aquaculture (Fig. 5e, f; Table II).

Spatialization of land use processes

The state of Maranhão has the largest area of mangrove forest (63%) and salt flats (87%) (Table III). By contrast, the state of Pará had a slight majority (51%) of the disturbed areas of mangrove forest. In Pará, however, salt flats are well preserved, representing only 0.01% of land use (Table III). Despite the fact that the mangroves of the study region are well-preserved overall,

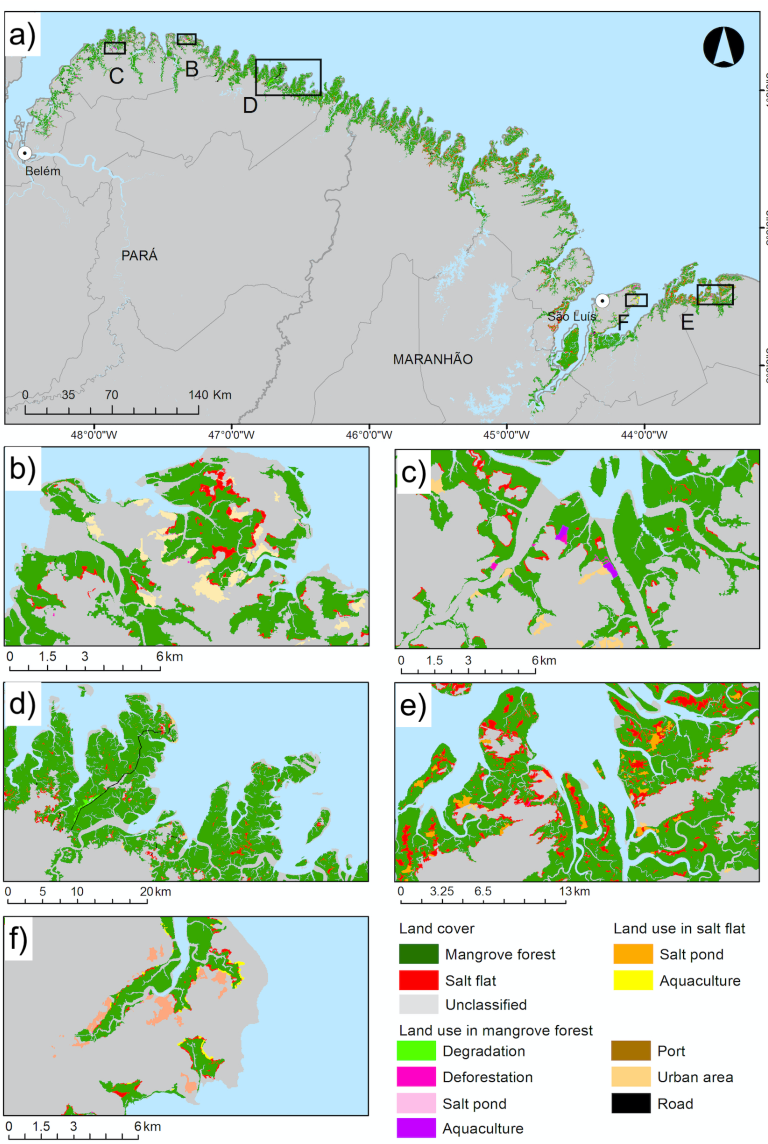


Figure 5. a) Classification of the different types of land cover and land use on the Brazilian Amazon coast. Examples of land use in the mangrove forest: b) urban development, c) aquaculture, d) deforestation, roads, and degradation, e) salt ponds in salt flats, and f) salt ponds in mangrove forest.

high concentrations of land use were recorded in the Salgado microregion, in Pará, and in the metropolitan region of São Luís, in Maranhão (Table IV; Fig 6a and 6b). The best-preserved mangroves are located in the Bragantina and Guamá microregions (Pará) and in the Gurupi and Baixada Maranhão microregions, in Maranhão (Fig. 6).

Urban development was the anthropogenic activity responsible for the most extensive impact on the Brazilian Amazon coast (48.28 km^2), followed by the construction of roads (2.43 km^2), degradation (1.68 km^2), and deforestation (1.19 km^2) (Table II). Degradation was only mapped in the Bragantina microregion, where it was derived from the construction of the PA-458 state highway (Fig. 7, Table IV). Aquaculture is found

Table II. Land cover and land use area in the mangrove forest and salt flats highlighting the different types of use.

Class	Area (km^2)	Land Cover/ Use (%)	Total (%)
LAND COVER			
Mangrove Forest (total)	7210.07	92	92
Mangrove forest	*6676.83*	*86*	-
Mangrove forest under cloud	*533.24*	*6*	-
Salt flat	542.88	7.17	7.15
Land cover Area	**7752.94**	**-**	**99.15**
LAND USE			
Mangrove Forest			
Deforestation	1.19	2.2	0.015
Degradation	1.68	3.1	0.022
Road	2.43	4.4	0.031
Urban area	48.28	88.2	0.617
Port	0.27	0.5	0.003
Salt pond	0.42	0.8	0.005
Aquaculture	0.46	0.8	0.006
Total	**54.73**	**-**	0.70
Salt Flat			
Salt pond	12.04	97.3	0.154
Aquaculture	0.33	2.7	0.004
Total	**12.38**	-	0.150
Land use area	**67.11**	**-**	**0.85**
TOTAL	**7820.05**		100

Table III. Area (km^2) and percentage (%) of land cover and land use of mangrove and salt flats in the states of Pará and Maranhão.

UF	**Mangrove forest**				**Salt flat**			
	Land cover		***Land use***		***Land cover***		***Land use***	
	(km^2)	**(%)**	**(km^2)**	**(%)**	**(km^2)**	**(%)**	**(km^2)**	**(%)**
Pará	2644.00	37	27.66	51	71.95	13	0.001	0.01
Maranhão	4566.06	63	27.07	49	470.93	87	12.379	99.99
Total	7210.07		54.73		542.88		12.38	

in the mangrove forest, typically in small areas (0.46 km^2), more evident in Pará, specifically in the Salgado microregion (Table IV; Fig. 5b, 5c and 6a). All the salt flat zones mapped were adjacent to areas of mangrove and high lands (Fig. 5e). Most of the land use in the salt flats was related to the construction of salt evaporation ponds (12.04 km^2), with only a small area dedicated to aquaculture (0.34 km^2). Most (52.27%) of the area of salt flat converted to human use was recorded in the Lençóis Maranhenses microregion and microregion of the west coast of Maranhão, with 27.19% (Table IV; Fig. 5e). This indicates that aquaculture is concentrated in the urban zone of the municipality of São Luís (Fig. 7, Table IV). It is important to note that the anthropogenic use of salt flats in Maranhão corresponded to only 3% of the total area of this type of habitat in this state. This value is well within the limits established by the Brazilian Forest Code for the conversion of salt flats in the coastal states of the Amazon (10%) and other coastal zones in Brazil (35%).

DISCUSSION

Analysis of the remote sensing images

Based on the methodological approach adopted in the present study, it was possible to map and quantify the land use processes in the mangroves of the Brazilian Amazon coast. This approach combined high-resolution data from RapidEye images and GEOBIA analysis became possible to map the mangrove forests, salt flats, and their respective anthropogenic uses with good global accuracy and high Kappa indices, for both the individual classes and the overall classification. The RapidEye images proved adequate for this mapping because they have a high spatial resolution (5 m), which permits the detection of the conversion of mangroves with great accuracy, and because they contain the red-edge band, which is recommended for measuring

Table IV. Area of the mainland uses in the Brazilian Amazon mangrove forest and salt flat in the context of the microregions in the states of Pará and Maranhão. Def. = deforestation, Deg = degradation, Aqua = Acquaculture, SP = salt pond, MF = mangrove forest area, SF = salt flat, and MR = microregion area. TMF = total mangrove forest area, TSF = total salt flat area, and TMR = total micro region area.

	MANGROVE FOREST									SAL FLAT				TMR	
	Def	**Deg**	**Urban**	**Road**	**SP**	**Aqua**	**Port**	**TMF**		**Aqua**	**SP**	**TSF**			
	(km^2)	**(km^2)**	**(km^2)**	**(km^2)**	**(km^2)**	**(km^2)**	**(km^2)**	**(km^2)**	**%**	**(km^2)**	**(km^2)**	**(km^2)**	**%**	**(km^2)**	**%**
Pará State															
Belém	0.07		2.48		0.04		0.17	0.48	1	0.001	-	0.001	0.01	2.76	4
Castanhal			1.65	0.06				4.78	9	-	-	-	-	1.71	2
Salgado	0.46		16.62	0.47		0.35	0.03	17.93	33	-	-	-	-	17.93	27
Bragantina	0.10	1.68	2.25	0.74			0.01	1.71	3	-	-	-	-	4.78	7
Guamá	0.01		0.45	0.02				2.76	5	-	-	-	-	0.48	1
Total Pará State	**0.64**	1.68	23.45	1.29	0.04	0.35	0.21	-		0.001					
Maranhão State															
Gurupi	0.05		1.00	0.18				2.22	4	-	0.48	0.48	3.88	2.70	4
Western littoral of Maranhão	0.07		6.94	0.48	0.28	0.01	0.03	7.81	14	0.004	4.6	4.60	37.19	12.41	18
São Luís	0.17		12.9	0.16	0.1	0.1	0.03	13.46	25	0.33	0.15	0.48	3.88	13.94	21
Rosário	0.21		1.72	0.3				2.23	4	0.003	0.34	0.34	2.77	2.57	4
Lençóis Maranhenses	0.05		1.28	0.02				1.35	2	0.001	6.47	6.47	52.27	7.82	12
Total Maranhão State	**0.55**	**1.68**	**24.83**	**1.14**	**0.38**	**0.11**	**0.06**	**-**		0.34	12.04				
GRAND TOTAL	1.19	1.68	48.28	2.43	0.42	0.46	0.27		100	0.34	12.04		100	67.11	100

the variation in vegetation cover (Schuster et al. 2012) and for mapping areas of mangrove forest (Meneghetti et al. 2014). The mapping of anthropogenic land use in the Amazonian mangrove forests and their associated salt flats showed that the areas affected by these activities are very small, as aquaculture tanks, or very narrow, such as the highway corridors. Although the segmentation well matched the limits of the target areas in the RapidEye images, the spectral response of some anthropogenic activities presented a high degree of similarity. Given the need to discriminate these activities, visual interpretation was crucial for the reliable classification of the objects.

While the RapidEye images facilitate the identification and visual discrimination of the target areas of anthropogenic land use in mangrove ecosystem, they also have certain limitations, which should be recognized for the more reliable mapping of the mangroves of the Brazilian Amazon coast. Firstly, the persistence of cloud cover in tropical regions may lead to underestimates of land cover and use when optical sensor images are analyzed. The mapping of large areas that requires the evaluation

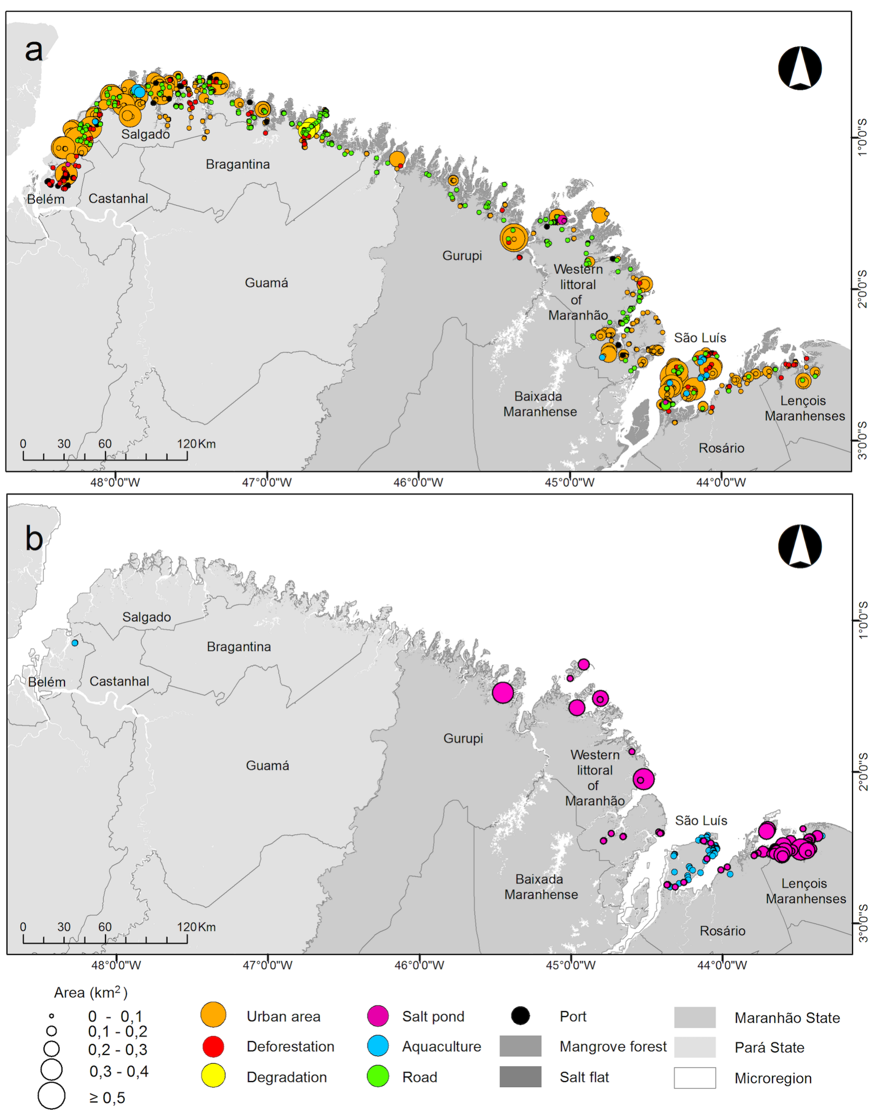


Figure 6. Distribution of different types of land use in mangrove forests (a) and salt flats (b) on the Brazilian Amazon coast.

of a mosaic of images from different years is another major challenge. It is also important to note here that it was also not possible to detect the other types of land use described by Fernandes et al. (2018), such as selective logging by local communities for the construction of fish weirs, the extraction of building material, and the production of charcoal. Given this, other types of satellite images with a higher spatial resolution (e.g., WorldView-3 with 0.3 m in spatial-resolution) will be essential for the detection of selective logging in coastal forests such as mangroves in multitemporal analyses of land cover and use in Amazonian mangroves.

Status of the mangroves land use on the Brazilian Amazon coast

The extension of the area of mangrove defined here from the RapidEye images is consistent with the findings of the previous studies of Souza-Filho (2005) and Nascimento et al. (2013). Results of the present study also reinforce the conclusion that the mangroves of the Brazilian Amazon coast are well preserved and that anthropogenic activities affect less than 1% of this region. This value is much lower than those recorded in other regions of Brazil (Ferreira & Lacerda 2016) and in Southeast Asia (Giri et al. 2008, Kanniah et al. 2015). In addition to the low level of anthropogenic impact in the mangroves

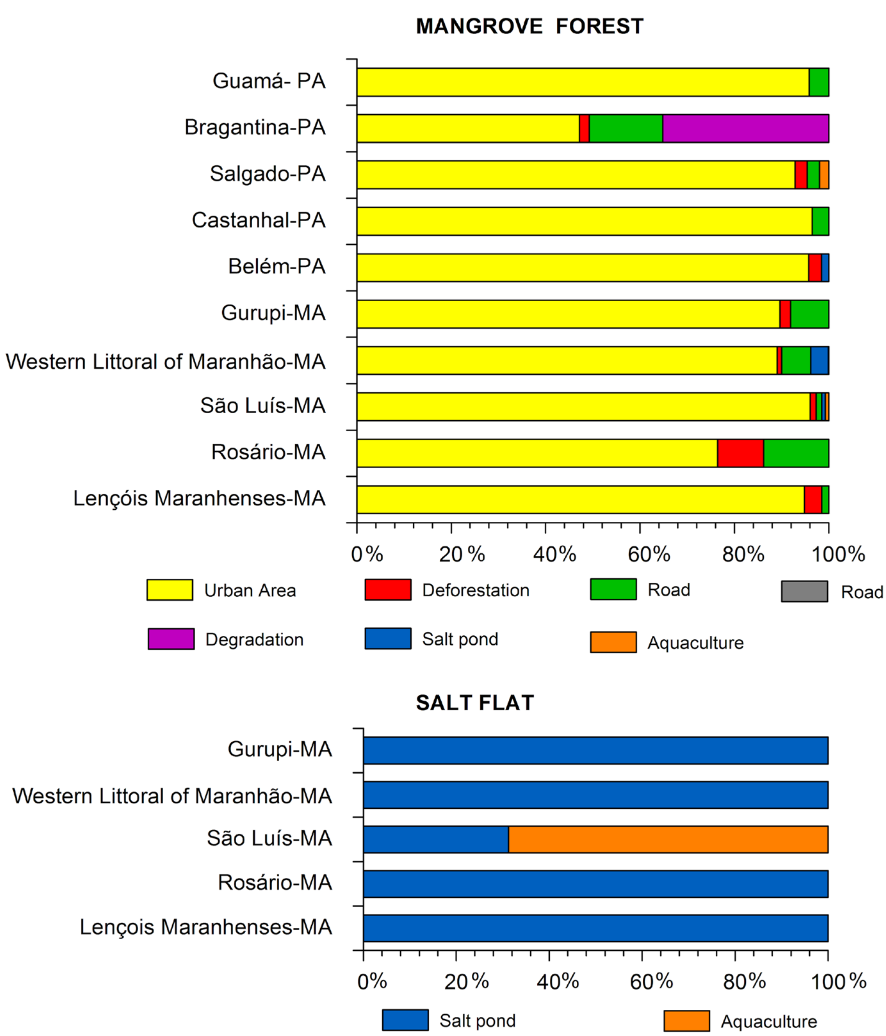


Figure 7. Percentage of the area occupied by different types of land use in the mangrove forest and salt flat of the different microregions in the Brazilian states of Pará and Maranhão.

of the Brazilian Amazon coast, the results of the present study indicate that urban development and road construction were the main drivers of the loss of mangroves in this region. This scenario is almost certainly related to the characteristics of the coastal zone, such as its low population density and the heterogeneous distribution of its population, with large, unoccupied expanses, interspersed with some areas of high population density (Szlafsztein 2009). In this context, urban expansion into the Amazonian mangrove forests is clearly due to local anthropogenic pressure, through the establishment of settlements in border areas between the mangrove forests or salt flats and the adjacent areas of tropical rainforest. On the other hand, the results also show that aquaculture is the least important driver of mangrove conversion in this region, corroborating the findings of Tenório et al. (2015). This contradicts the general tendency observed in other regions of Brazil, where the expansion of aquaculture, together with other forms of agriculture, is the primary driver of the conversion of mangrove habitats (Leão et al. 2018, Ferreira & Lacerda 2016, Queiroz et al. 2013). A similar trend has been observed in another countries (Primavera et al. 2019), including Thailand, Myanmar, Bangladesh, and Sri Lanka (Giri et al. 2008), China (Meng et al. 2016), Indonesia (Malik et al. 2017), and India (Jayanthi et al. 2018).

The conservation of the Amazonian mangroves may be related to the regulation of mangroves by the Brazilian Forest Code, as well as the presence of a number of conservation units in this region. Even so, the region's extremely low population density and the lack of basic infrastructure have unquestionably played a key role in the maintenance of this ecosystem over time. The synergy of all these factors has permitted the conservation of the largest continuous tract of mangrove in the world. The Brazilian Forest Code (Federal Law no. 12,651/2012), together with the characterization of mangroves as an area of permanent preservation (Brasil 2012), has legally assured the maintenance of the ecosystem, its biodiversity, and the well-being of the local human populations. This has been reinforced by the establishment of conservation units, including 12 extractive reserves, four environmental protection areas, one national park, and one sustainable development reserve, on the Brazilian Amazon coast. These protected areas have provided support for the maintenance of the socioeconomic and cultural needs of the traditional estuarine-coastal communities, enabling the organization of land use, and the protection of the goods and services provided by mangroves (ICMBio 2018).

The population of the coastal zone of the Salgado microregion represents only 8% of the total population of Pará (Szlafsztein 2009), which contrasts with the situation found in other Brazilian states, where 40% of the population typically inhabits the coastal zone (Ferreira & Lacerda 2016). In general, the traditional estuarine-coastal communities of this region depend on subsistence activities, such as small-scale fisheries (Fernandes et al. 2018) and family farming (Krause 2010). The preservation of the mangrove in this region is also related to the lack of the infrastructure, including paved highways and a power grid (Hayashi et al. 2019), that tends to accelerate the human settlement and exploitation of natural resources (such as fish and lumber) in areas of mangrove. The lack of other infrastructure, such as shipping terminals, industries, and in particular, shrimp farming operations, has also limited the loss of mangrove habitat in the region (Fernandes et al. 2018). It is also important to make clear, to both local communities and policy makers, that intact mangroves are a far more valuable resource than those converted to other uses (Van Lavieren et al. 2012). In this case, preventative rather than recuperative strategies should be considered the principal priority in all cases.

The Brazilian Forest Code defines salt flats as a distinct environment from the mangrove (Brasil 2012). From a legal standpoint, then, salt flats are not considered to be part of the mangrove and, therefore, are not considered to be an area of permanent preservation, but rather, 10% of their area can be exploited in an ecologically sustainable way. In other words, salt flats are vulnerable to exploitation for activities such as salt production and shrimp farming, and all such activities that were initiated prior to July 22nd, 2012, are now legitimate, after publication of the Brazilian Forest Code. Given this set of factors, then, salt flats are more vulnerable to being occupied by saltworks and shrimp farms (Diniz & Vasconcelos 2017, Oliveira & Freitas Filho 2017).

Recommendations for mangrove conservation and sustainability

Given the scenario of environmental conservation observed in the areas of mangrove on the Brazilian Amazon coast, it is important to support the management of the goods and services provided by these ecosystems. This requires management plans that establish effective technical measures and standards for human use and occupation, which respect the limitations of coastal environments. The findings of the present study point to a number of measures that will contribute to the development of these management strategies, such as:

the implementation of new studies to better understand the geographic distribution of anthropogenic activities in the mangrove, and their social and environmental impacts, as well as to analyze more systematically the anthropogenic pressures affecting the surrounding areas, adjacent to the mangroves;

the analysis of the effectiveness of the conservation units in this region to assess whether they are, in fact, fulfilling their role as protected areas;

the development of new methods for the detection of the other human activities that could not be detected in this study, such as the mapping of the scars left by the selective logging in the mangroves used to supply raw materials for the construction of buildings and fishing weirs, and the production of charcoal.

CONCLUSIONS

The mangroves of the Brazilian Amazon coast can be considered to be well preserved, given that less than 1% of their total area is impacted by anthropogenic activities. Urban expansion and the construction of roads were the principal drivers of impacts on the mangroves in this region, supported by local anthropogenic pressures through the establishment of settlements at the margin between the mangrove forests and the adjacent salt flats or the dry land forests. On the other hand, aquaculture, the principal activity responsible for the loss of mangroves in other South American and Asian countries, plays a secondary role in the region of the Amazon coast. The salt-flat zones are disturbed only in the state of Maranhão, for the industrial production of salt, although the negative impacts are much reduced in comparison with the other states of northeastern Brazil. This activity nevertheless demands especially close attention, given that it is legally sanctioned by the Brazilian Forest Code. Overall, our findings provide a better understanding of the conservation status of the mangroves on the Brazilian Amazon coast, and a useful approach for the definition of mangrove land cover and use from high-resolution satellite images using an approach that includes visual interpretation and object-oriented classification, which can be replicated easily in other coastal zones, worldwide.

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REFERENCES

ASP NE ET AL. 2018. Sediment dynamics of a tropical tide-dominated estuary: Turbidity maximum, mangroves and the role of the Amazon River sediment load. Estuar. Coast. Shelf Sci 214: 10-24. https://doi.org/10.1016/j.ecss.2018.09.004.

BAATZ M & SCHÄPE A. 2000. Multiresolution Segmentation: an optimization approach for high quality multi-scale image segmentation, in: Strbl J & Blaschke T (Eds), Angewandte Geographische Informationsverarbeitung. Wichmann, Heidelberg, p. 12-23.

BRASIL. 2012. Lei n° 12.651, de 25 de Maio de 2012. BRASIL.

CÁRDENAS, NY, JOYCE KE & MAIER SW. 2017. Monitoring mangrove forests: Are we taking full advantage of technology? Int J Appl Earth Obs Geoinf 63: 1-14. https://doi.org/10.1016/j.jag.2017.07.004.

CARNEY J, GILLESPIE TW & ROSOMOFF R. 2014. Assessing forest change in a priority West African mangrove ecosystem: 1986-2010. Geoforum 53: 126-135. https://doi.org/10.1016/j.geoforum.2014.02.013.

CONGALTON RG. 1991. A review of assessing the accuracy of classifications of remotely sensed data. Remote Sens Environ 37: 35-46. https://doi.org/10.1016/0034-4257(91)90048-B.

CONGALTON RG & GREEN K. 2009. Assessing the Accuracy of Remotely Sensed Data : Principles and Practices, 2nd ed., CRC Press - Taylor & Francis Group, Boca Raton, Florida.

COUGO MF, SOUZA-FILHO PWM, SILVA AQ, FERNANDES MEB, SANTOS JR, ABREU MRS, NASCIMENTO WR & SIMARD M. 2015. Radarsat-2 backscattering for the modeling of biophysical parameters of regenerating mangrove forests. Remote Sens 7: 17097-17112. https://doi.org/10.3390/rs71215873.

DI GREGORIO A. 2005. Land Cover Classification System: Classification concepts and user manual. UNEP-FAO: Roma.

DINIZ C, CORTINHAS L, NERINO G, RODRIGUES J, SADECK L, ADAMI M & DOUZA-FILHO PWM. 2019. Brazilian mangrove status: three decades of satellite data analysis. Remote Sens 11: 2-19. https://doi.org/10.3390/rs11070808.

DINIZ MTM & VASCONCELOS FP. 2017. Condicionantes naturais à produção de sal marinho no Brasil. Mercator 16: 1-19. https://doi.org/10.4215/rm2017.e16013.

FAO. 2007. The world's mangroves 1980-2005. FAO For Pap, n. 153. Roma, 89 p. https://doi.org/978-92-5-105856-5.

FERNANDES MEB ET AL. 2007. Efeito da construção da rodovia pa-458 sobre as florestas de mangue da península bragantina, Bragança, Pará, Brasil. Uakari 3: 55-63.

FERNANDES MEB, OLIVEIRA FP & EYZAGUIRRE IAL. 2018. Mangroves on the Brazilian Amazon Coast: Uses and Rehabilitation. In: MAKOWSKI C & FINLL C (Eds), Threats to Mangrove Forests. Coastal Research Library, v 25. Springer, Cham, p. 621-635. https://doi.org/10.1016/j.ocecoaman.2016.03.011.

FERREIRA AC & LACERDA LD. 2016. Degradation and conservation of Brazilian mangroves, status and perspectives. Ocean Coast Manag 125: 38-46. https://doi.org/10.1016/j.ocecoaman.2016.03.01.

FOODY GM. 2002. Status of land cover classification accuracy assessment. Remote Sens Environ 80: 185-201. https://doi.org/10.1016/S0034-4257(01)00295-4.

FREITAS D, RAMOS AKA, SANO EF, BORGES RKM & SILVESTRE KS. 2018. Mapas dos manguezais do Brasil. In: ICMBIO (Ed) Atlas dos Manguezais do Brasil. ICMBIO: Brasília, p. 121-174.

GIRI C, LONG J, ABBAS S, MURALI RM, OAMER FM, PENGRA B & THAU D. 2015. Distribution and dynamics of mangrove forests of South Asia. Journal of Environ Manage 148: 101-111. https://doi.org/10.1016/j.jenvman.2014.01.020.

GIRI C, OCHIENG E, TIESZEN LL, ZHU Z, SINGH A, LOVELAND T, MASEK J & DUKE N. 2011. Status and distribution of mangrove forests of the world using earth observation satellite data. Glob Ecol Biogeogr 20: 154-159. https://doi.org/10.1111/j.1466-8238.2010.00584.x.

GIRI C, ZHU Z, TIEZEN LL, SNGH A, GILLETTE S & KELMLIS JA. 2008. Mangrove forest distributions and dynamics (1975-2005) of the tsunami-affected region of Asia. J Biogeogr 35: 519-528. https://doi.org/10.1111/j.1365-2699.2007.01806.x.

HADLICH GM, CELINO JJ & UCGA JM. 2010. Diferenciação físico-química entre apicuns, manguezais e encostas na Baía de Todos os Santos, Nordeste do Brasil. Geociências 29: 633-641. http://repositorio.ufba.br/ri/handle/ri/7325.

HAMILTON SE & CASEY D. 2016. Creation of a high spatio-temporal resolution global database of continuous mangrove forest cover for the 21st century. Glob Ecol Biogeogr 25: 729-738. https://doi.org/10.1111/geb.12449.

HAYASHI SN, SOUZA- FILHO PWM, NASCIMENTO WR & FERNANDES MEB. 2019. The effect of anthropogenic drivers on spatial patterns of mangrove land use on the Amazon coast. PLoS ONE 14: 1-20. https://doi.org/10.1371/journal.pone.0217754.

IBGE. 1990. Divisão regional do Brasil em mesorregiões e microrregiões geográficas. Rio de Janeiro: IBGE, 137 p. https://doi.org/10.1017/CBO9781107415324.004.

ICMBio. 2018. Atlas dos Manguezais do Brasil, 1nd ed., Brasília: Instituto Chico Mendes de Conservação da Biodiversidade, 179 p.

JAYANTHI M, THIRUMURTHY S, MURALIDHAR M & RAVICHANDRAN P. 2018. Impact of shrimp aquaculture development on important ecosystems in India. Glob Environ Change 52: 10-21. https://doi.org/10.1016/j.gloenvcha.2018.05.005.

KANNIAH KD, SHEIKHI A, CRACKNELL AP, GOH HC, TAN KP, HO CS & RASLI FN. 2015. Satellite images for monitoring mangrove cover changes in a fast growing economic region in southern Peninsular Malaysia. Remote Sens 7: 14360-14385. https://doi.org/10.3390/rs71114360.

KRAUSE G. 2010. The Geography of the Bragança Coastal Region. In: SAINT-PAUL U & SCHNEIDER H (Eds), Mangrove Dynamics and Management in North Brazil. Ecological Studies (Analysis and Synthesis), v 211. Springer, Berlin, Heidelberg, p. 19-34. https://doi.org/10.1007/978-3-642-13457-9_3.

LANG S, SCHOPFER E & LANGANKE T. 2009. Combined object-based classification and manual interpretation - Synergies for a quantitative assessment of parcels and biotopes. Geocarto Int 24: 99-114. https://doi.org/10.1080/10106040802121093.

LEAO AR, PRATES APL & FUNI M. 2018. Manguezais e as Unidades de Conservação. In: ICMBIO (Ed), Atlas dos Manguezais do Brasil, ICMBIO: Brasília, Brasil, p. 105-119.

MA Z & REDMOND RL. 1995. Tau coefficient for accuracy assessment of Classification of remote sensing data. Photogramm Eng Remote Sens 61: 435-439.

MALIK A, MERTZ O & FENSHOLT. 2017. Mangrove forest decline: consequences for livelihoods and environment in South Sulawesi. Reg Environ Chang 17: 157-169. https://doi.org/10.1007/s10113-016-0989-0.

MENEGHETTI GT, JOHANN H & KUX H. 2014. Mapeamento da cobertura da terra no município de Raposa (MA) utilizando imagens Worldview-II ,o aplicativo interimage e mineração de dados. Rev Bras Cartogr 66: 365-377. https://doi.org/10.1016/j.orggeochem.2016.06.001.

MENEZES MPM DE, BERGER U & MEHLIG U. 2008. Mangrove vegetation in Amazonia: a review of studies from the coast of Pará and Maranhão States, north Brazil. Acta Amaz 38: 403-420. https://doi.org/10.1590/S0044-59672008000300004.

MENG X, XIA P, LI Z & MENG D. 2016. Mangrove degradation and response to anthropogenic disturbance in the Maowei Sea (SW China) since 1926 AD: Mangrove-derived OM and pollen. Org Geochem 98: 166-175.

MMA. 2015. Geocatálogo-MMA: Catálogo de Imagens de Satélite RapidEye do Ministério do Meio Ambiente. Available at: < http://geocatalogo.mma.gov.br/> Assessed in June 2015.

MORAES BC, COSTA JMN, COSTA ACL & COSTA MH. 2005. Variação espacial e temporal da precipitação no Estado do Pará. Acta Amaz 35: 207-214. https://doi.org/10.1590/S0044-59672005000200010.

NASCIMENTO WR, SOUZA-FILHO PWM, PROISY C, LUCAS RM & ROSENQVIST A. 2013. Mapping changes in the largest continuous Amazonian mangrove belt using object-based classification of multisensor satellite imagery. Estuar Coast Shelf Sci 117: 83-93. https://doi.org/10.1016/j.ecss.2012.10.005.

OLIVEIRA LMM & FREITAS FILHO MR. 2017. Quantificação dos ambientes de apicum e salgado na planície fluviomarinha do rio Coreaú/CE à luz do novo código florestal. Caminhos Geográficos 18: 184-201. https://doi.org/10.14393/RCG186308.

PANET. 2018. Planet Imagery product specification: Planetscope & Rapideye. Available at: < https://www.planet.com > Assessed in January 2018.

PLESNIK J, HOSEK M & CONDÉ S. 2011. A concept of a degraded ecosystem in theory and practice – a review. ETC/BD Working paper N° A/2011, Paris, France: European Environment Agency (EEA), p. 12.

PRIMAVERA JH, FRIESS DA, VAN LAVIERE H & LEE SY. 2019. The Mangrove Ecosystem, 2nd ed, World Seas: an Environmental Evaluation. Elsevier, p. 1-34. https://doi.org/10.1016/B978-0-12-805052-1.00001-2.

QUEIROZ L, ROSSI S, MEIRELES J & COELHO C. 2013. Shrimp aquaculture in the federal state of Ceará, 1970-2012: Trends after mangrove forest privatization in Brazil. Ocean Coast Manag 73: 54-62. https://doi.org/10.1016/j.ocecoaman.2012.11.009.

RIDD PV & STIEGLITZ T. 2002. Dry season salinity changes in arid estuaries fringed by mangroves and saltflats. Estuar Coast Shelf Sci 54: 1039-1049. https://doi.org/10.1006/ecss.2001.0876.

RODRIGUES SWP & SOUZA-FILHO PWM. 2011. Use of multi-sensor data to identify and map tropical coastal wetlands in the amazon of Northern Brazil. Wetlands 31: 11-23. https://doi.org/10.1007/s13157-010-0135-6.

SANTOS L, MATOS H, SCHAEFFER-NOVELLI Y, UNHA-LIGNON M, BITENCOURT M, KOEDAM N & DAHDOUH-GUEBAS F. 2014. Anthropogenic activities on mangrove areas (São Francisco River Estuary, Brazil Northeast): a GIS-based analysis of CBERS and SPOT images to aid in local. Ocean Coast Manag 89: 39-50. http://dx.doi.org/10.1016/j.ocecoaman.2013.12.010.

SCHAEFFER-NOVELLI Y, CINTRON-MOLERO G & SOARES MLG. 2002. Mangroves as indicators of sea level change in the muddy coasts of the world. In: HEALY T, WANG Y & HEALY J-A (Eds) Muddy Coasts of the World: Processes, Deposits and Function, New York: Springer, p. 245-262.

SCHAEFFER-NOVELLI Y, RAVAI AS, COELHO C, MENGHINI RP & ALMEIDA R. 2012. Alguns impactos do PL no30/2011 sobre os manguezais brasileiros. In: Comitê Brasil em Defesa das Florestas e do Desenvolvimento Sustentável (Ed). Código Florestal e a Ciência: O que nossos legisladores ainda precisam saber. Brasília: Comitê Brasil. Brasília-DF.

SCHMIDT AJ, BEMVENUTI CE & DIELE K. 2013. Sobre a definição da zona de apicum e a sua importância ecológica para populações de caranguejo-uça, *Ucides cordatus*. Bol Técnico-Científico do CEPENE 19: 9-25.

SCHUSTER C, FORTER M & KLEINSCHMIT B. 2012. Testing the red edge channel for improving land-use classifications based on high-resolution multi-spectral satellite data. Int J Remote Sens 33: 5583-5599. https://doi.org/10.1080/01431161.2012.666812.

SOUZA-FILHO PWM. 2005. Costa de manguezais de macro mare da Amazônia: cenários morfológicos, mapeamento e quantificação de áreas usando dados de sensores remotos. Rev Bras Geociênc 23: 427-435. http://dx.doi.org/10.1590/S0102-261X2005000400006.

SOUZA-FILHO PWM & EL-ROBRINI M. 2000. Geomorphology of the Braganca coastal zone, northeastern Para State. Rev Bras Geociênc 30: 522-526.

SOUZA-FILHO PWM, SANTOS JR WRN & SANTOS DC. 2018. A GEOBIA Approach for Multitemporal Land-Cover and Land-Use Change Analysis in a Tropical Watershed in the Southeastern Amazon. Remote Sensing 10: 1-22. https://doi.org/10.3390/rs10111683.

SZLAFSZTEIN CF. 2009. Indefinições e obstáculos no gerenciamento da Zona Costeira do Estado do Pará. Revista da Gestão Costeira Integrada 9: 47-58. https://doi.org/10.5894/rgci114.

TENÓRIO GS, SOUZA-FILHO PWM, RAMOS EMLS & ALVES PJO. 2015. Mangrove shrimp farm mapping and productivity on the Brazilian Amazon coast: Environmental and economic reasons for coastal conservation. Ocean Coast Manag 104: 65-77. https://doi.org/10.1016/j.ocecoaman.2014.12.006.

UCHA JM, HADLICH GM & CELINO JJ. 2008. Apicum: transição entre solos de encostas e de manguezais. Revista ETC Educação, Tecnologia e Cultura 5: 58-63.

VAN LAVIEREN H, SPALDING M, ALONGI D, KAINUMA M, CLÜSENER-GODT M & ADEEL Z. 2012. Securing the Future of Mangroves: A Policy Brief. UNU-INWEH, UNESCO-MAB with ISME, ITTO, FAO, UNEP-WCMC and TNC, Okinawa, Japan, 53 p.

SUPPLEMENTARY MATERIAL

Figures S1, S2.
Tables SI, SII, SIII.

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