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A MULTI-TEMPORAL REMOTE SENSING AND GIS BASED INVENTORY OF THE MANGROVES AT ITAMARACÁ ESTUARINE SYSTEM, NORTHEASTERN BRAZIL

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RESUMO

Embora estejam sob proteção legal, os manguezais do Brasil vêm sendo paulatinamente reduzidos, quer por ações diretas (aterros, desmatamento, ocupação para fins residenciais, turísticos e agro-aqüícolas) ou indiretas (poluição dos cursos fluviais). Nesse estudo foram usadas imagens de satélite e SIG para analisar a distribuição dos manguezais ao longo do sistema estuarino de Itamaracá, Nordeste do Brasil, além de identificar as mudanças ocorridas na vegetação, no período entre 1974-2001. A abordagem utilizada para estimar as alterações na área ocupada por manguezais, considerada uma variável contínua, foi baseada no método de classificação supervisionada em imagens multiespectrais e multi-temporal SPOT/HRV e Landsat7/ETM+. Ortofotocartas, mapeamento dos recursos hídricos superficiais e informações obtidas em campo foram utilizados como fontes complementares de dados. Áreas preservadas de floresta mangue (4.118,01 ha), *apicum* (397,28 ha), lavado (464,77 ha) e fazendas de camarão (484,05 ha) foram obtidas a partir de dados ETM+ (2001), em Itamaracá, Goiana, Itapissuma, Igarassu. A análise temporal foi realizada em 64% da área global de estudo, para os anos 1974, 1996 e 2001. No período de 27 anos (1974-2001), verificou-se uma diminuição da área de floresta de manguezal em torno de 11,06%. A taxa anual de desmatamento do manguezal foi de 0,42% (1974-1996) e 0,28% (1996-2001). Áreas ocupadas por fazendas de camarão cresceram 394,12% entre 1996 e 2001, a uma taxa média anual de 66,67%. O coeficiente kappa e a exatidão global do mapa temático produzido pelo método de classificação foi de 0,97 e 98,56% (ETM+) e 0,95 e 97,38% (SPOT), respectivamente. O uso do sensoriamento remoto e SIG mostraram-se eficientes para detectar alterações ocorridas nas áreas de manguezais e fornecer importantes informações para tomada de decisão, além de propor ações voltadas para o desenvolvimento sustentável das atividades costeiras, no sistema estuarino de Itamaracá.

Palavras-Chave: Manguezais. Sensoriamento remoto. SIG. Fazenda de camarão. Itamaracá. Brasil.

ABSTRACT

Despite being under legal protection, the quantity of Brazilian mangroves has been gradually reduced, because of either direct actions (landfills, deforestation, urban expansion, tourism, agriculture, and aquaculture activities) or indirect actions (pollution of rivers). Control and law enforcement in mangrove areas require continuous monitoring, which is difficult to accomplish from ground and/or water based surveys. In this study, satellite images and GIS were used to analyze the distribution of mangroves along the Itamaracá estuarine system in Northeastern Brazil, beyond identifying changes in vegetation from 1974 to 2001. The approach used to estimate changes in the area occupied by mangroves as a continuous variable was based in the supervised classification method in multispectral and multi-temporal SPOT/HRV and Landsat7/ETM+ data. Orthophotomaps, superficial hydric resources mapping, and field data were used as

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complementary data sources. Regions of preserved mangrove forest (4118.01 ha), salt flats (397.28 ha), mud flats (464.77 ha), and shrimp farms (484.05 ha) were computed from ETM+ data (2001) in Itamaracá, Goiana, Itapissuma, and Igarassu cities. Temporal analysis was carried out in 64% of the global study area for the years 1974, 1996, and 2001. Based on GIS analysis over the 27 years (1974-2001), the area of the mangrove forest was found to have decreased by 11.06%. The annual rate of mangrove deforestation was 0.42% (1974-1996) and 0.28% (1996-2001). Areas occupied by shrimp farms expanded by 394.12% between 1996 and 2001 at a mean annual rate of 66.67%. The kappa coefficient and the overall accuracy of the thematic map produced by the classification method was 0.97 and 98.56% (ETM+) and 0.95 and 97.38% (SPOT), respectively. Application of remote sensing and GIS proved to be efficient to detect changes of mangrove areas and provide relevant information to guide decisions and propose actions concerning sustainable development of coastal activities in the Itamaracá estuarine system.

Keywords: Mangrove. Remote sensing. GIS; Shrimp farm. Itamaracá. Brazil.

INTRODUCTION

The Brazilian coast extends for 8698 km and has a mean population density of 121 inhabitants km^2 (MMA, 2007). The coastal region is used for numerous different, and sometimes conflicting, types of activities (Moraes, 1999). The coast of the Pernambuco State has a population density of 971 inhabitants km^2, which is the highest in the country (Marroni and Asmus, 2005). One of the environmental problems threatening the Pernambuco coast is mangrove deforestation by anthropic activity.

The Itamaracá estuarine system, in Northern Pernambuco State, was formed during the early Holocene. A fault flooded by the South Atlantic Ocean seawaters created the Santa Cruz Channel and formed Itamaracá Island. Mangrove forests occupy the lowlands along the inner portion of the Santa Cruz Channel and the shores of the lower tributaries. Despite being of socio-economic relevance as source of food and income for the nearby population, the mangroves have been continuously threatened by pollution (Meyer et al., 1998; Telles, 2001) and removed to make room for urban expansion (summer residences, roads, hotels, and marinas) and aquaculture activities (CPRH, 2001). The Itamaracá estuary is characterized by an extensive area with difficult access. Control and law enforcement in mangrove areas require continuous monitoring, which is difficult to accomplish from ground or water-based surveys.

The rapid changes in the region require the use of techniques to enable the extraction of information and the maintenance of monitoring programs in operational terms, at affordable costs. Within these constraints, remote sensing emerges as a technology that presents synoptic and spectral information that is conducive to temporal analyses. Geographic Information System (GIS) analysis can quickly process spatial data generated from remote sensing and provide computational model that simulate processes occurring in the geographic space (D'Alge, 2007).

Coastal and estuarine zones receive special attention in many countries which use integrated studies to assist management actions (Clark, 1995). Conservation of these ecosystems, considered as Permanent Preservation Areas (PPA) by the Brazilian Forest Code (BRASIL. Law n. 4.771, 1965), has been the focus of several studies (Schaeffer-Novelli, 1999; Siqueira Filho, 1998; Machado, 1991; Maciel, 1991) – below will be presented some details about the Brazilian Federal Law theory. International treaties also make reference to the subject, such as the Ramsar Convention (1971), which proposed the conservation of wet zones and the sustainable use of their resources.

In the present study, we use remote sensing data and GIS to identify and determine the distribution of mangroves in the Itamaracá estuarine system, NE-Brazil, as well as to detect and analyze their changes between 1974 and 2001. The methods used differs from the others by providing information about areas of the components of the mangroves' ecosystem (mangrove forest, salt flats, and mud flats) and possibilities the analyses from the ground-truth samples. Analyses in scientific and juridical terms are performed to differentiate these components using satellite images, and to assist in the management of the estuarine and coastal areas.

THEORETICAL FRAMEWORK

Mangroves are composed of zones of vegetation (mangrove forest), mud flats (submersed zone at high water), and salt flats or "apicum" (more elevated zones in the soil, generally sandy, occurring at the midlittoral/supralittoral interface and, rarely, in the forest interior), that are closely related in geological, geomorphological, physical, chemical, and biological terms (Bigarella, 1947; Maciel, 1991; Nascimento, 1993; Schaeffer-Novelli, 1999; Pachêco, 2002). According to these researchers, these features may be considered as belonging to the same system.

Article 2 of the Brazilian Federal Law of Forest Code considers forests and the other natural vegetation forms located in the restingas that serve as dune or mangroves stabilizers to be areas of permanent preservation (BRASIL. Law n. 4.771, 1965). At that time, the term "mangrove" referred only to the vegetation. In later legal documents (BRASIL. CONAMA n. 303, 2002), the term "mangrove" was extended, which led to an interpretation that salt flats areas and mangrove forest are part of the same ecosystem. However, as a rule, imprecise legal definitions concerning the distinct forms of the mangrove ecosystem have permitted the management institutions in Pernambuco State to adopt measures that do not consider the salt flats area as a part of the mangrove.

Because of this perspective, a resolution by the state of Pernambu-co (PERNAMBUCO. CONSEMA n. 002, 2002) authorizes partial (30%) occupation of the salt flats areas for the purpose of shrimp farm installations. This conflicts with the resolution that expressly prohibits this activity in mangrove areas (BRASIL. CONAMA n. 312, 2002). In the present study, mangrove forest areas, salt flats, and mud flats are considered as parts of the mangrove ecosystem.

The magnitude of losses of mangroves is a global concern. Anthropic alterations by conversion of mangroves to mariculture, agriculture, and urbanization (Saenger et al., 1983) and natural factors such as an increase sea level (Ellison, 1993) have threatened the mangrove habitats. The world's area of mangrove forest has been reduced by about 35% since 1980s, and these losses translate into an annual loss of 2.1% (Valiela et al, 2001).

In some states in northeast Brazil, use of remote sensing techniques indicated that shrimp farm areas represent one of the factors responsible for suppression of the mangroves (Cavalcanti et al., 2007; Carvalho, 2004; Crepani and Medeiros, 2003). According to CPRH (2001), the aquaculture activity has generated conflicts of use with the local population that depends on the mangrove resources.

Beyond deforestation, studies showed that mangroves absorb the waste generated by the shrimp farms (Wosten et al., 2003) and that shrimp farms add nutrients to mangrove forests through water and sediment discharge (Thu and Populus, 2007). Thus, monitoring is needed to verify if waste and nutrients discharged during artisanal fishing damages the fauna present in the mangroves or causes alterations in the water and sediments in the Itamaracá region. According to Wang et al. (2003), it is necessary to conduct studies on the functions of the mangrove ecosystem and on the density of its forests in order to address biological questions of sustainable development.

STUDY AREA

The Itamaracá Estuarine System is situated between the UTM coordinates 9,159,994.454 mN to 9,131,334.400 mN and 286,028.487 mE to 301,028.517 mE (Geodesic Reference System for the Americas, or SIRGAS). This area includes the city of Itamaracá and portions of the cities of Igarassu, Itapissuma, and Goiana (Fig. 1). The area is within the GL-1 group of the coastal hydrographic basins in Pernambuco State, NE-Brazil.

The study region has a hot and wet climate, defined as type Aws' by the Köppen system of climate classification. It has an annual mean temperature of 26°C and an annual precipitation of 1500 mm because it is under the influence of the southeast trade winds (Medeiros and Kjerfve, 1993). The system receives the drainage of the Catuama, Itapessoca, Arataca, Botafogo, Congo, Igarassu, and Paripe Rivers via the Santa Cruz Channel, which connects to the Atlantic Ocean through the Catuama Inlet, in the North and through the Orange Inlet, in the South. A single river, the Jaguaribe, drains Itamaracá Island and discharges directly into the Atlantic Ocean.

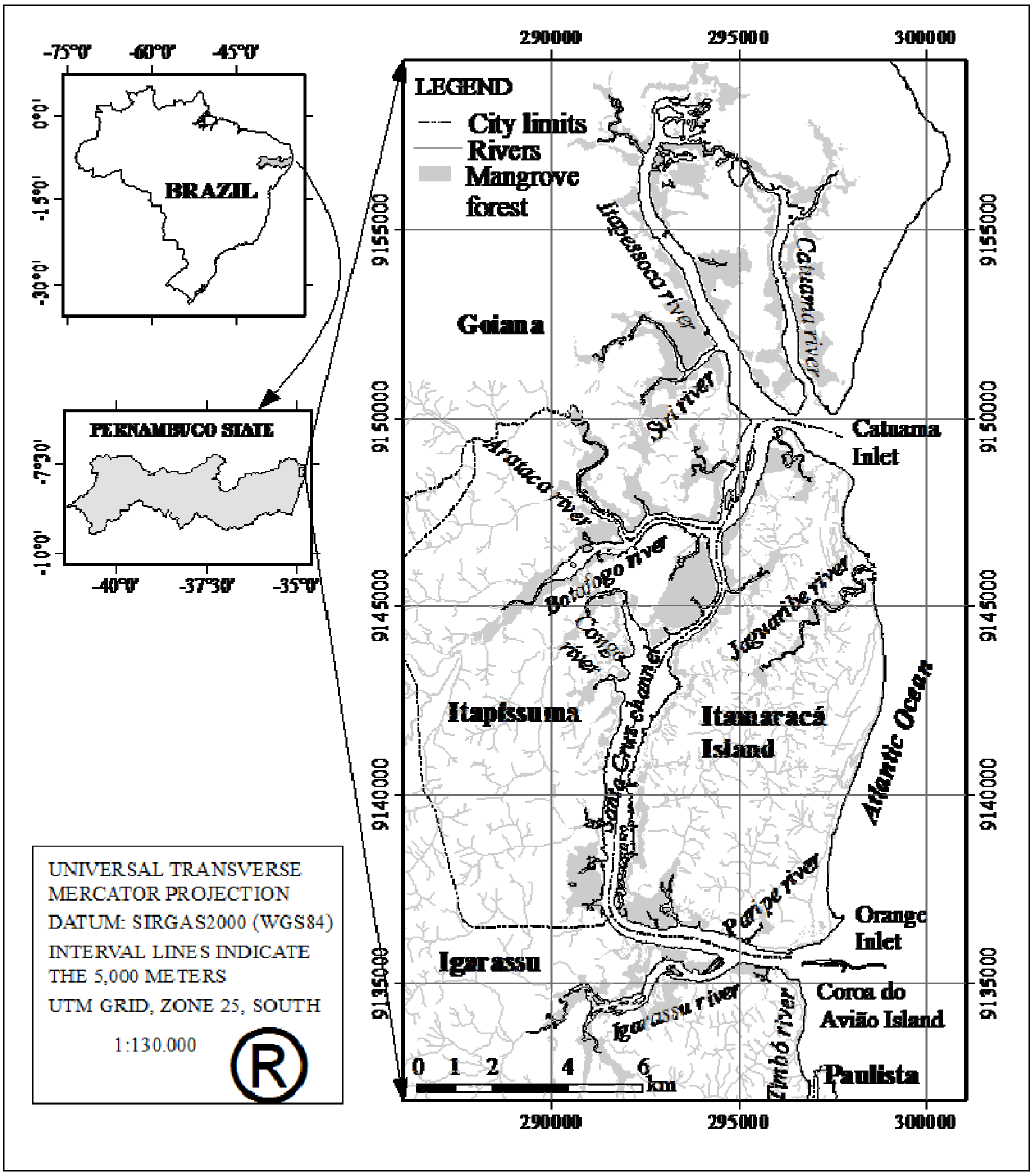

Figure 1 - Itamaracá estuarine system, northeastern Brazil.

Mangroves occupy the inner portion of the Santa Cruz channel and along the lower sections of the rivers. The dominant species are *Rhizophora mangle* (red mangrove), *Laguncularia racemosa* (white mangrove), and *Avicennia shaueriana* (black mangrove) (Medeiros et al., 2001), with some occurrences of *Conocarpus erectus* (bud mangrove) (Silva, 1995). The local economy is mainly based on tourism, artisanal fishing, and industrial, agricultural, and aquacultural activities.

MATERIAL AND METHODS

Materials

The data were extracted from four main sources: (1) orthophotomaps from 1974 (scale 1:10000, UTM: Córrego Alegre, zone 25, South), which contain planialtimetric information; (2) mapping of superficial hydric resources in the Metropolitan Region of Recife, carried out from aerial photographs from 1974 (scale: 1:10000, UTM: Córrego Alegre, Zone 25,South) (CONDEPE/FIDEM, 1978); (3) images from Satellite Pour l'Observation de la Terre / High-Resolution Visible (SPOT/HRV) multispectral (20 m), with three bands from August 22^{nd}, 1996 and panchromatic (10 m) from July 20, 1998; and (4) multispectral images (30 m) and panchromatic (15 m) from the Landsat7/ Enhanced Thematic Mapper Plus (ETM+) satellite from August 4^{th}, 2001. ETM+ images were provided by the University of Maryland (http://glcfapp.umiacs.umd.edu:8080/esdi/index.jsp). The orthophotomaps and cartographic mapping were obtained from the Agency Planning and Research State of Pernambuco (CONDEPE/FIDEM).

Ground-based observations

Field and aerial surveys were performed to confirm the analyzed targets. The identification of the targets aided in the choice of the training areas that were used in the supervised classification process. Deforested mangrove forest areas and expanded areas of shrimp farms were detected and georrefenced during the 2003 and 2004 flights (Fig. 2).

Figure 2 - Aerial photographs of mangrove deforestation and shrimp farms in the deployment phase in the Itamaracá system (CPRH,2003; Moura, 2004).

Transformation methodology for the Geodesic Reference System for the Americas (SIRGAS)

Recently, Brazil adopted a Geocentric Reference System through the Brazilian Institute of Geography and Statistics (IBGE) that permits the localization of any object on the Earth, taking as a reference the center of mass of the Earth. This new system, called the Geocentric Reference System for the Americas (SIRGAS), is compatible with the precision of positioning methods (Global Navigation Satellite Systems - GNSS) (IBGE, 2005).

Originally, the coordinates of the orthophotomaps were in Brazilian Local Reference System Corrego Alegre. After transformation, the remote sensing data were compatible with each other in relation to the geodesic system SIRGAS 2000 and the UTM projection system. The data transformation from the Corrégo Alegre system (international ellipsoid of Hayford 1924) for the GRSA2000, was performed in two steps: (1) use of the GT87 software (Management of the Army's Geographic Services) to transform the data from the Córrego Alegre system to SAD-69 system (South American Datum of 1969), and (2) use of the TCGeo software (Brazilian Institute of Geography and Statistcs - IBGE) to transform the data from the SAD-69 to the GRSA 2000. The parameters used in the transformations are described in Table 1.

Table 1. Transformation parameters of the systems CÓRREGO ALEGRE-SAD-69 and SAD-69-GRSA2000 (IBGE,2005)

PARAMETERS		CÓRREGO ALEGRE to SAD-69 (m)	SAD-69 to SIRGAS (m)
Greater semi-axis of the ellipsoid from the origin system	a_1	6,378,388.00	6,378,160
Ellipsoid flattening from the origin system	f_1	1/297.00	1/298.25
Greater semi-axis of the ellipsoid on the fate system	a_2	6,378,160.00	6,378,137
Ellipsoid flattening on the fate system	f_2	1/298.25	1/298.257222101
Transformation parameter among systems	Δx	-138.7	-67.35
Transformation parameter among systems	Δy	+164.40	+3.88
Transformation parameter among systems	Δz	+34.40	-38.22

Methodology to identify mangroves by remote sensing and GIS

Recent studies have used remote sensing techniques integrated with GIS to determine how the characteristics of mangrove forest distribution change over time in different countries (Thu and Populus, 2007; Rajintha et al., 2007; Wang et al., 2003; Murray et al., 2003).

These studies have provided important data about sustainable development. In other recent studies, digital image processing methods (Lillesand and Kiefer, 1994) were applied to detect mangrove forests change (Giri et al., 2007; Thampanya et al., 2006; Berlanga-Robles and Ruiz-Luna, 2002; Ramírez-Garcia et al., 1998; Green et al., 1997). In general, a measure of the performance of classification by satellites images may be obtained from the classification error matrix (Congalton et al., 1983). The kappa estimator (Ponzini and Almeida, 1996; Ramírez-Garcia et al., 1998; Berlanga-Robles and Ruiz-Luna, 2002) can then be used to quantitatively evaluate that matrix (Lillesand and Kiefer, 1994). The techniques in the present paper are based on these studies, and are used to obtain the distinct components (mangrove forest, salt flats, and mud flats) in the Itamaracá estuarine system.

Band composition and image integration

Spectral band combinations 1, 2, 3, 4, 5, and 7 (30 m) from the Landsat ETM+ data were tested. In addition, edge enhancement filtration was applied in order to choose combinations of the three bands (R,G,B) which better resolve the targets of interest for the current study. The enhancenment was applied with histogram adjustments for RGB combinations 3,2,1 (HRV) and 7,4,1 (ETM+). To improve the spatial resolution and data interpretation, panchromatic and multspectral images from Landsat ETM+ and SPOT were fused (merge resolution), permitting integration of images from different spatial resolutions (pixel size). This was performed using the techniques of principal components and nearest-neighbor resampling (Lillesand and Kiefer, 1994).

Image registration

Registration of the images consisted of resampling the pixels according to a coordinate system that assumes features of scale and projection of a certain cartographic basis. Orthophotomaps (scale 1:10000) were used as the cartographic basis, from which ground control points (GCPs) were taken to reference the images (Lillesand and Kiefer, 1994). The GCPs were homogeneously distributed across the study area when possible. There were difficulties in this step due to the orthophotomaps and cartographic maps for the region being out of date.

Digital image processing for preliminary analyses

Image processing techniques used in this article are based on the row imagery DNs (digital numbers). These techiniques were applied to perform preliminary analyses such as image enhancement, filtering, unsupervised classification, and principal components analyses to make the decorrelation and to generate new RGB combination with more contrast among the targets, and to aid in the process of visual interpretation and image classification. Application of contrast by linear transformation to the images permitted enhancement the studied targets, and information obtained by unsupervised classification helped in verifying the image interpretation with field observations.

Supervised classification

The classification procedure consisted of automatically categorizing all the pixels of an image into classes or themes, which define the cover of the terrestrial surface. For the supervised classification process, four classes (mangrove forest, tidal flat, water bodies, and “others”) were established to extract the mangrove ecosystem. The class “others” includes all the features in the image, which were not considered in the process of supervised classification, such as the shrimp farm and salt flat/*apicum*, for presenting heterogeneous pixels. Thus, salt flat areas and shrimp farm were extracted from the visual interpretation of SPOT and Landsat images.

Training areas were selected based on the enhancement to obtain a better discrimination of the image category from preliminary analyses results and field information. The samples were extracted by homogeneous polygons digitalization (> 200 pixels, except for the tidal flat category) over the image, and codified agreed with each classe. The spectral pattern of each class was used as the numerical basis for the categorization. Thus, the different types of targets manifested different digital levels combinations (DN), based on their own inherent properties of spectral reflectance (Lillesand and Kiefer, 1994). Finally, supervised classification which uses the spectral information from the pixels to recognize homogeneous polygons, was used to process the images.

Evaluation on the classification accuracy

Classification performance used in this article was evaluated by a matrix of classification error, which compares the relation between the reference data (ground truth) and the results obtained by automatic classification category by category (Lillesand and Kiefer, 1994). Some descriptive measures such as overall accuracy, producer’s accuracy, user’s accuracy, omission errors, and commission errors were obtained from the error matrix to evaluate the classification of the SPOT and ETM+ images (Tables 2 and 3). Overall accuracy of the classification was calculated by dividing the total number of pixels correctly classified (sum of principle diagonal elements) by the total number of sampled pixels (n). This value is obtained by applying the equation:

$$overall \cdot accuracy = \sum_{i=1}^{c} x_{ii} / n \qquad (1)$$

where c is the number of categories or classes and x_{ii} is the number of pixels correctly classified for each category. Similarly, accuracies of individual categories were calculated by dividing the number of pixels correctly classified in each category by the total number of pixels sampled in the corresponding column (producer's accuracy) or line (user's accuracy).

The errors that occurred in the classification process are represented by the non-diagonal elements in the matrix. Omission errors (E_o) correspond to the non-diagonal elements in the column and indicate the number of pixels which should have been classified and were excluded from the category. In the same way, commission errors (E_{co}) are represented by the non-diagonal elements in the line, which indicate the pixels which were incorrectly included in a category.

$$E_o = (x_{+i} - x_{ii}) / x_{+i} \qquad (2)$$

$$E_{co} = (x_{i+} - x_{ii}) / x_{i+} \qquad (3)$$

where x_{+i} is the number of pixels sampled in column i and x_{i+} is the number of pixels sampled in line i.

The kappa estimator $\hat{k}$ was used as an indicator of the concordance measure to evaluate the classification error matrix. This measure is based on the difference between the real accuracy (observed between the reference data and an automatic classification) and the accuracy that would be obtained by random estimation (between the reference data and a random classification) (Lillesand and Kiefer, 1994). The kappa estimator can have values between $0 < \hat{k} < 1$. As kappa approaches 1, classification improves. Mathematically, this is calculated by:

$$\hat{k} = N\sum_{i=1}^{r} x_{ii} - \sum_{i=1}^{r} (x_{i+} \cdot x_{+i}) / N^2 - \sum_{i=1}^{r} (x_{i+} \cdot x_{+i}) \qquad (4)$$

where: $N\sum_{i=1}^{r} x_{ii}$ = observed accuracy; $\sum_{i=1}^{r} (x_{i+} \cdot x_{+i})$ = chance agreement; r **=** number of lines in the error matrix; x_{ii} = number of observations in the line i and column i; x_{i+} = total observations in the line i; x_{+i} = total observations in the column i; and N **=** total number of observations included in the matrix. The kappa estimator incorporates the non-diagonal elements of the matrix as the product of the marginal lines and columns, as opposed to the total accuracy index, which considers only the diagonal elements from the error matrix.

Image post-classification

A statistical filter with a 3x3 mask based on the major statistical parameters was used in the post classification step to reduce the noise in the classified image (Jensen, 1996). This option use a low frequency filter to remove the isolated pixels, and caused no alterations in the original form of their polygons (classified targets). Procedures such as information checking and class recodification were performed to correct errors generated in the classification process.

Mangrove forest from cartographic mapping

Mangrove forest was digitized from the Mapping of Surface Hydric Resources of Metropolitan Region of Recife (CONDEPE/FIDEM, 1978), which contains information on superficial hydric resources. The 1974 maps were used to adjust the information obtained in the mapping described above.

Nine orthophotomaps from 1974 were scanned and transposed to a digital format and then subsequently transformed into mosaics. Geometric correction was performed with the ground control points (GCPs) distributed throughout the mosaic image. Reference coordinates for image registration were obtained from the orthophotomaps. A maximum RMS error of 1 pixel (0.85 m) was accepted for the transformation (UTM: Córrego Alegre, Zone 25, South). They were then transformed to the geodesic reference system (GRSA) SIRGAS2000 (WGS84). The areas corresponding to the shrimp farms were taken from the orthophotomaps that were already in digital format and interpretation of satellite image.

GIS analysis

GIS may be defined as "a powerful set of programs for collection, storing recuperation under demand, transformation and presentation of spatial data in the real world for a particular purpose" (Burrough and Mcdonnell, 1998). In this study, spatial data modeling was performed according to Sá (2001). The spatial data were defined (mangrove forest areas, salt flats, and shrimp farms) and included their spatial position (coordinate system), spatial attributes (characteristics of spatial data), spatial relation (mangrove x shrimp farms), and time (analysis between 1974-2001, temporal variation of 27 years). Hydrographic networks and level curves of 2 m were digitalized from the hydric resources mapping and orthophotomaps, respectively, and overlain the images. These procedures were used to eliminate the errors generated by the automatic classification in the mangroves extraction. In the step following the post-classification, analyses of data in the GIS database were used to generate attribute tables for each category.

RESULTS AND DISCUSSIONS

Image processing

The spatial registration obtained from the SPOT and Landsat ETM+ images was precise, having an average residual error (RMS) of less than 0.5 pixels. SPOT and Landsat images are considered acceptable for transformation and are adequate for temporal analysis of mangrove forest cover (Thu e Populus, 2007; Giri et al., 2007; Wang et al., 2003). The infrared bands 4R, 5G, 7B in the Landsat ETM+ image (Fig. 3a), and the two visible bands and 1 of the near infrared 3R, 2G, 1B bands in the SPOT image (Fig. 3b), showed good qualitative results for the visual identification of the categories analyzed, which is important in the process of target recognition of the supervised classification. Salt flats areas were obtained from the bands' combinations in the visible and infrared spectra in the SPOT and ETM+ images. With image classification, it was possible to perform measurements and obtain data about the mangrove forest areas, salt flats, mud flats, and shrimp farms.

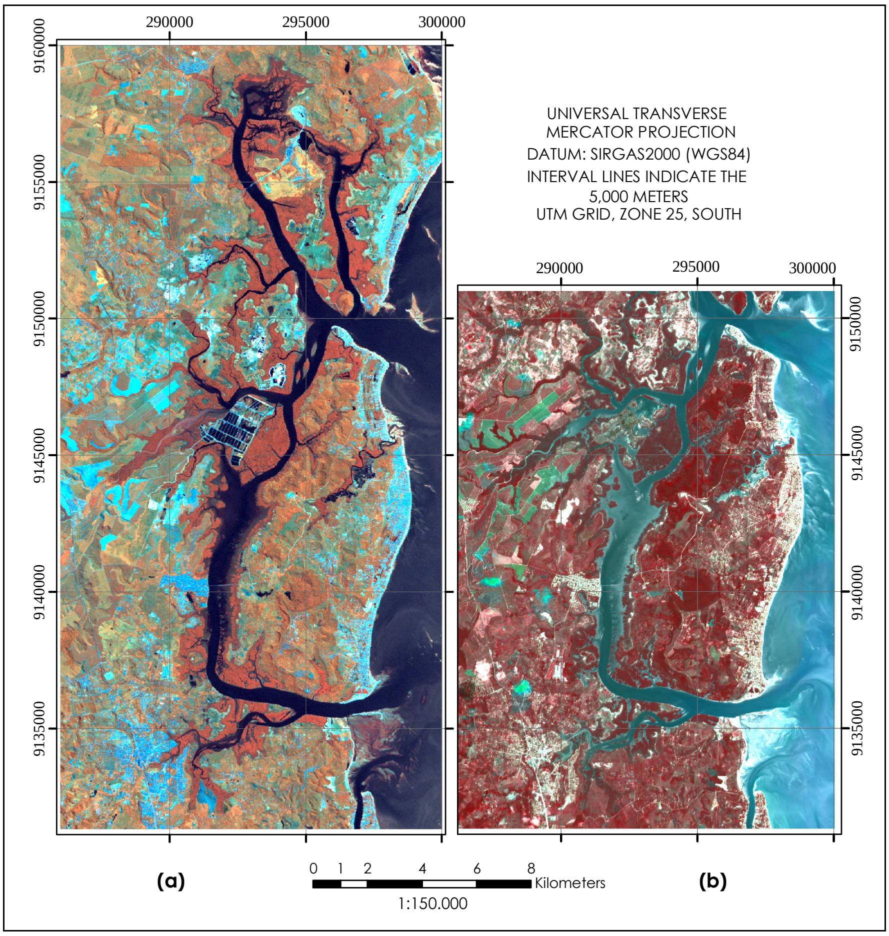

Figure 3 - (a) Landsat ETM+ image 2001 (4R, 5G, 7B). (b) SPOT 1996 image (3R, 2G, 2B).

The quality of the supervised classification was determined by the proximity of the thematic information when compared to the original image data. According the evaluation on the classification, a total of 7343 pixels in the SPOT images and 3061 pixels in the ETM+ images were used to quantitatively evaluate the classification results (Tables 2 and 3), which were confirmed by the ground truth verification. Among the pixels sampled, 7151 pixels (SPOT) and 3017 pixels (ETM+) were part of the principal diagonal of the error matrix, representing an agreement of about 97.38% and 98.56% (global accuracy) between the reference and classified data for the SPOT/HRV and ETM+ images, respectively.

Table 2. Error matrix, overall accuracy, omission and commission errors, producer's accuracy, user's accuracy, and kappa coefficient resulting from classification of 1996 SPOT image of the Itamaracá coastal zone, Brazil.

	Reference data						
Classification data	**Mangrove forest**	**Mud flat**	**Water bodies**	**Other classes**	**Row total**	**User's accuracy (%)**	**Commission errors (%)**
MANGROVE FOREST	1470	0	0	8	1478	99.46	0.54
MUD FLAT	0	458	172	0	630	72.70	27.30
WATER BODIES	1	10	4086	0	4097	99.73	0.27
OTHER CLASSES	1	0	0	1137	1138	99.91	0.09
COLUMN TOTAL	1472	468	4 258	1145	7343		
PRODUCER'S ACCURACY (%)	99.86	97.86	95.96	99.30			

OMISSION ERRORS (%)	0.14	2.14	4.04	0.70

Overall accuracy = 97.38%; Kappa coefficient = 0.95

Table 3. Error matrix, overall accuracy, omission and commission errors, producer's accuracy, user's accuracy, and kappa coefficient resulting from classification of 2001 Landsat ETM+ image of the Itamaracá coastal zone, Brazil.

	REFERENCE DATA						
Classification data	**Mangrove forest**	**Mud flat**	**Water bodies**	**Other classes**	**Row total**	**User's accuracy (%)**	**Commission errors (%)**
MANGROVE FOREST	627	0	0	31	658	95.29	4.71
MUD FLAT	0	77	0	0	77	100	0
WATER BODIES	0	3	1338	0	1341	99.78	0.22
OTHER CLASSES	1	0	9	975	985	98.98	1.02
COLUMN TOTAL	628	80	1347	1006	3061		
PRODUCER'S ACCURACY (%)	99.84	96.25	99.33	96.92			
OMISSION ERRORS (%)	0.16	3.75	0.67	3.08			

Overall accuracy = 98.56%; Kappa coefficient = 0.97

The analysis shows in general, individual classes (mangrove forest, mud flats, water bodies, and other classes) had low omission and commission errors for both images. The results of mangrove forest category had producer's accuracy 99.86% (SPOT) and 96.25% (ETM+) and omission errors of 0.14% (2 of 1472 pixels for SPOT) and 0.16% (1 of 628 pixels for ETM+). Excessive delimitation of this category provided 99.46% (SPOT) and 95.29% (ETM+) user's accuracy and commission errors higher than the omission errors: 0.54% (8 of 1478 pixels for SPOT) and 4.71% (31 of 658 pixels for ETM+).

Mangrove forests of the Itamaracá estuarine system (including the Santa Cruz Channel (SCC) and Jaguaribe River estuaries) had a total area of 4118.01 ha in 2001. Mangrove areas covered 4515.29 ha, when including salt flats areas (397.28 ha) for the same period. We used the GIS function summary to produce statistics that compared the areas of the classes between two thematic archives (cities and classification), including the amount and percentages of common area. This provided the spatial distribution of the categories analyzed for each city. Mangroves exist in the cities of Goiana, Itapissuma, and Igarassu (Table 4) and represent 10.5% of the total study area (Fig. 1). Mangrove forest areas and salt flats areas distributed along the SCC estuary covered 4036.94 ha and 391.24 ha, respectively. In the Jaguaribe estuary, the computed areas were 81.07 ha of mangrove forest and 6.07 ha of salt flats. There were 484.05 ha of shrimp farms in the study area in 2001.

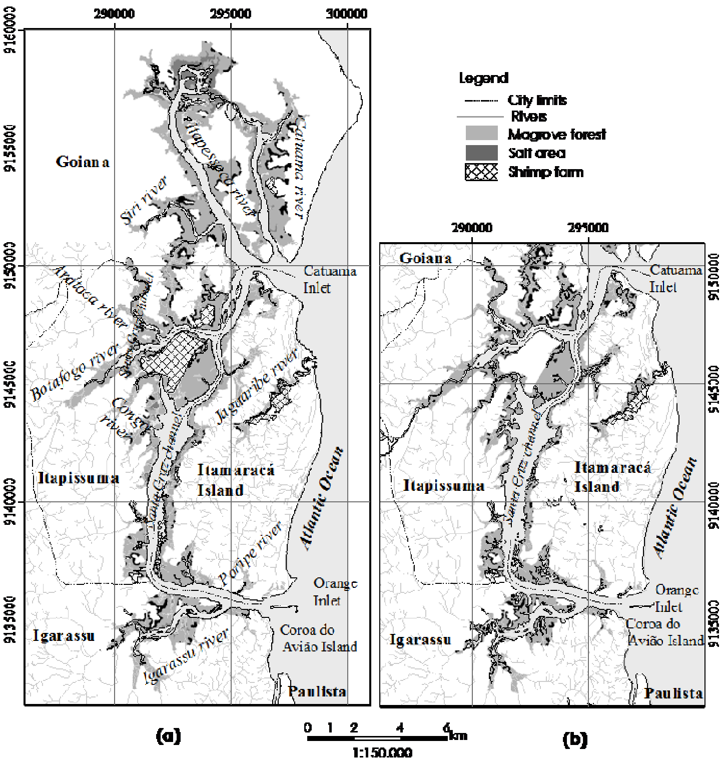

Figure 4 - (a) Classification Landsat ETM+ image (2001). (b) Classification SPOT image (1996).

SPATIAL DISTRIBUTION OF MANGROVE IN 2001

Table 4. Area of Mangrove forest and shrimp farms areas at Itamaracá, Goiana, Itapissuma and Igarassu (2001).

Cities	Mangrove forest (ha)	Salt flats (ha)	Mud flats (ha)	Shrimp farms (ha)
ITAMARACÁ	715.36	32.75	79.97	89.05
GOIANA	1982.77	262.14	286.34	70.80
ITAPISSUMA	975.54	49.66	68.88	321.41
IGARASSU	444.34	52.73	29.58	2.79

SPATIO-TEMPORAL DISTRIBUTION OF MANGROVE

The study area was reduced to 64% of the study area (Figure 1) due to absence of orthophotomaps in the north coastal zone of Itamaracá. This area situated between the UTM coordinates 9,151,000 N to 9,131,340 N and 286,000 E to 300,000 E (Geodesic Reference System for the Americas, or SIRGAS). Temporal evaluation of mangrove distribution was performed for the years 1974, 1996, and 2001, using the orthophotomaps and SPOT and EMT+ images.

To solve the different spatial resolutions of the images of 1974, 1996, and 2001, the results of the analysis are presented in percentages of classified areas with reference to the total area.

Data comparison between the periods shows a 9.55% reduction in the mangrove forest areas in 22 years (1974-1996) and 1.67% in 5 years (1996-2001), with average annual reduction rates of 0.42% and 0.28%, respectively. Between 1974 and 2001 there was an 11.06% reduction in the area of mangrove forests.

The spatial distribution of the mangrove forest in Itamaracá, Itapissuma, Igarassu, and part of Goiana, is referenced to 1974, 1996, and 2001 (Table.5). Was observed that the highest vegetation reduction of 26.69% in Igarassu (1974-2001), with a 1.06%

annual average deforestation rate. However, from 1996 to 2001, a small increase of mangrove forest areas was observed in Itamaracá due to natural regeneration of vegetation in abandoned shrimp farm ponds in the Jaguaribe River estuary (Moura, 2004). Fig.5 shows the image-based change analyses from mangrove forest spatial distribuition in 1974-2001 period.

Table 5. Percentage of mangrove forest areas in the cities (1974, 1996 and 2001).

Cities	Orthofotothomaps (1974)	Spot (1996)	Landsat etm+ (2001)
ITAMARACÁ	2.88%	2.57%	2.60%
GOIANA (partial area)	1.49%	1.59%	1.66%
ITAPISSUMA	3.92%	3.83%	3.54%
IGARASSU	2.29%	1.58%	1.61%
COLUMN TOTAL	10.58%	9.57%	9.41%

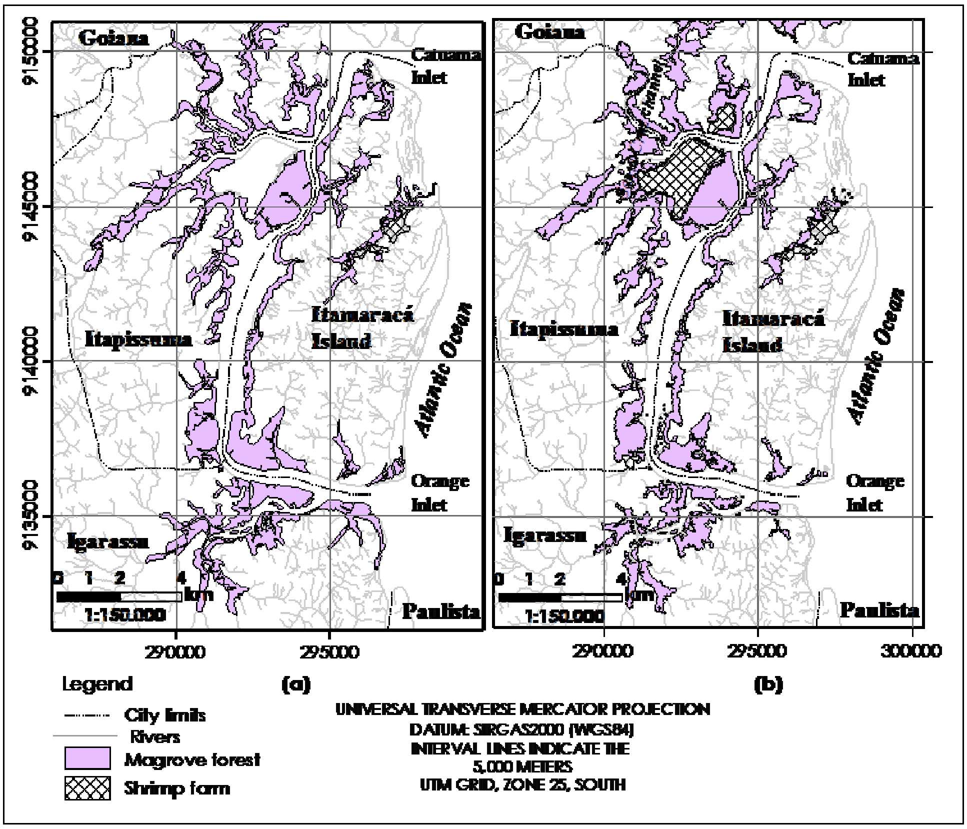

Figure 5 - Mangrove forest and shrimp farms spatial distribuition. (a) 1974. (b) 2001.

Analysis of the population data and areas occupied by mangrove forests and shrimp farms (Table 6), combined with observations of aerial photographs, satellite images, and the CPRH (2001) land use map, reveals that the removal of mangrove forests occurred to make room for the installation of shrimp farms and urban expansion. It is important to note that population (IBGE, 2007) growth does not necessarily occur in the neighborhood of mangroves.

Table 6. Population evolution and mangrove forest and shrimp farms occupation.

	1974	**1996**	**2001**
POPULATION **(**inhabitants)	113784	172001	189428
MANGROVE FOREST (%)	10.58%	9.57%	9.41%
SHRIMP FARMS (%)	0.34%	0.39%	1.68%

Areas occupied by shrimp farms in 1974, 1996, and 2001 were 0.34%, 0.39%, and 1.68%, respectively. The increase in aquaculture activity between 1996 and 2001, motivated by economic benefits, was 330.77%. This activity and factors previously mentioned (1974-1996) that contributed to the suppression of the mangrove forests and occupation of salt flats. This can be computed with remote sensing techniques and GIS. For example, a shrimp farm located in the northern part of Itamaracá Island, Goiana city, caused 2.4 ha of mangrove deforestation and 9.05 ha of salt flats occupation (Moura,2004).

Silva (2004) characterized and mapped sediments of the Santa Cruz bottom channel and identified changes in the pattern of deposition on the pattern found by Lira (1975). Most of the deposit which was formed in medium to coarse sand, we have found areas with deposits of medium to fine sand, and areas where previously mapped as deposits of fine sand, silt was found. According to Silva (2004), these changes probably occurred due to the deforestation of mangroves around the Santa Cruz channel for the shrimp farm installations. The mangrove retain fine sediment through their roots, and, when devastated, these sediments are carried to the channel. Another reason for the deforestation, would be related to the removal of sand from borders areas of the channel, for use in construction. This study adopted her characterization that corroborated with our evaluation using cited technique.

In fact, application of remote sensing and GIS to the Itamaracá system proved to be a valuable tool to map, inventory, and detect changes in the distribution of mangroves. This information could be used to assist law enforcement, guide management actions and planning, and to monitor conformities with international agreements such as the Ramsar Convention (Seto and Fragkias, 2007). In addition, these techniques are likely applicable to other similar areas.

CONCLUSIONS

The importance of mangrove ecosystems is legally recognized in Brazil, as they are considered protected areas by federal and state laws, however their application is rare. In the Itamaracá estuarine system, the difficulties of ground and/or water based monitoring surveys and terminology conflicts in the protection laws that regulate its use have resulted in the loss of 11.06% of the mangrove forest in a 27 years period due to deforestation and occupation of salt flats areas (1974-2001). This was mainly due to urban expansion and installation of shrimp farms, which reflect a population increase and the profit of the farming activities.

Results from the overall accuracy and kappa coefficient for mangrove classification using ETM+ and HRV/SPOT data indicated a good performance of the data processing techniques used.

The use of GIS made possible the manipulation of remote sensing products (thematic maps) and the use of descriptive data in the same database. Such a strategy seems appropriate for identifying and mapping the distribution of the mangroves. It also is appropriate for quantifying changes of mangrove forest, monitoring conformities with the international environmental agreements such those established at the Ramsar Convention, and generating information which may be used for making decisions on the management of coastal and mangrove areas.

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