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Anthropogenic activities on mangrove areas (São Francisco River Estuary, Brazil Northeast): A GIS-based analysis of CBERS and SPOT images to aid in local management

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ABSTRACT

In Brazil, despite the existence of various environmental laws to protect mangroves, this ecosystem has been affected by a variety of anthropogenic activities. The São Francisco River Estuary (SFRE, Brazil Northeast) comprises significant mangrove forests, important for human populations, and is included in an Environmental Protected Area of sustainable use which does not have a management plan. This work assessed and mapped anthropogenic activities on the mangroves of this estuary and provided a number of guidelines for a local management plan. Satellite images (SPOT 5 and CBERS 2B) of 2008 were processed and a land use/cover map (study area size: 192.4 km^2) produced and verified by fieldwork. About 93% (178.8 km^2) of the study area is occupied by natural cover such as: sandy coastal vegetation (147.3 km^2, 77%), mangroves (30.1 km^2, 15.7%) and intertidal flats (1.4 km^2, 0.7%), while 7% (13.6 km^2) is occupied by human activities as aquaculture (4.5 km^2, 2.4%) and agriculture (9 km^2, 4.7%). These uses are spatially distributed within mangroves, accounting for approximately one quarter (7.8 km^2) of its area, which may indicate the conversion of these forests. Shrimp farming is the main anthropogenic activity, occupying the highest area and occurring within the tallest *Rhizophora mangle* forests (tree height >15 m). We recommend that a management plan for the SFRE considers: the implementation of sustainable aquaculture practices (e.g. small-scale without deforestation of mangroves, use of native species, effluent treatment, socio-economic equity), strategies for the compliance of the laws regarding shrimp farming license and operation and support the creation of community-based cooperatives for the execution of sustainable aquaculture.

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1. Introduction

Mangroves are the only forests situated at the interface of land and sea in the world's subtropics and tropics coasts where they fulfil several valuable socio-ecological and economic services (Alongi, 2002; FAO, 2007). For example, mangrove forests act as a natural buffer, providing coastal land stabilization and protection against storms, tsunamis and sea level rise (e.g. Dahdouh-Guebas et al., 2005; Gilman et al., 2008; Feagin et al., 2010; Mukherjee et al., 2010). This ecosystem forms an ideal habitat for a variety of animal species, including commercially important species, thus supporting offshore fish populations and fisheries (Barbier, 2000; Nagelkerken et al., 2008). Furthermore, more than 90% of the world's mangroves are located in developing countries (Duke et al., 2007), where deprived human populations directly depends on a variety of mangrove and coastal resources, mainly fisheries, as source of income and subsistence (Walters et al., 2008).

The multiple uses of the coastal zone such as artisanal and commercial fisheries, aquaculture, agriculture, human settlements, harbours, ports, recreation, tourism, mining and industries have given rise to conflicts over resource uses (Primavera, 2006). For instance, due to pressures from anthropogenic activities, mangrove forests are disappearing worldwide at rates of 1–2% per year, which are as high as 3.6% in the Americas (Valiela et al., 2001; Alongi, 2002; FAO, 2003; Primavera, 2006; Duke et al., 2007). From these, aquaculture is one of the most controversial and considered one of the largest threats to mangroves (Alongi, 2002; Primavera, 2006), mainly because this activity have been developed without adequate management. Nevertheless, mangroves and aquaculture are not necessarily incompatible (Primavera, 2006), and studies have shown the development of more sustainable aquaculture practices which considers ecological, environmental and socio-economic aspects (e.g. Primavera, 2006; Bergquist, 2007; Guimarães et al., 2010; Haque et al., 2009; Martinez-Porchas and Martinez-Cordova, 2012).

Brazil, with a coastal zone of approximately 8 500 km of extent (4° 30′ N to 33° 44′ S), shows the third largest mangrove area in the world, accounting for 7% of this and 50% of South America mangroves (Asmus and Kitzmann, 2004; FAO, 2007; Magris and Barreto, 2010; Giri et al., 2011). Various decrees and laws in three levels of governance: federal (national), state (regional) and municipal (local) and by a decentralized system, legally enforce the conservation and management of Brazilian mangroves. At the federal level, the Forest Code (Brasil, 1965) and the National Council of Environment (CONAMA, 2002a) consider mangroves as Areas of Permanent Preservation and the National Coastal Management Plan (Brasil, 1988, 2004) prioritizes their conservation and protection (Magris and Barreto, 2010; Reis-Neto et al., 2011). In addition, conservation areas in coastal zones containing mangroves have been created by the National System of Conservation Units (Brasil, 2000, 2002). This system foresees that each conservation unit should implement a management plan, technical document which establishes the zoning and rules for the use of the area and natural resource management (Brasil, 2000). However, in practice, very few protected areas have such plans (Jablonski and Filet, 2008). Despite of the existence of these laws, Brazilian mangroves have been affected by a variety of anthropogenic activities, resulting in losses higher than 50.000 ha (Schaeffer-Novelli, 1991; FAO, 2007; Magris and Barreto, 2010).

The monitoring and environmental assessment of mangroves is a difficult management task, considering the inaccessibility of these areas and their mud substrate, which make difficult the achievement of fieldworks. In this context, remote sensing analysis within geographic information systems (GIS) is found to be a highly advantageous tool (Dahdouh-Guebas, 2002; Souza-Filho et al., 2006; Satyanarayana et al., 2011). Over the past 20 years, remote sensing has played a crucial role in mapping and understanding changes in the areal extent and spatial pattern of mangrove forests related to natural disasters and anthropogenic forces, providing fast, accurate and up-to-date baseline information on the status of this vegetation, which is a pre-requisite for sustainable development and conservation planning (Dahdouh-Guebas, 2002; Heuman, 2011; Nandy and Kushwaha, 2010). In this approach, satellites images have frequently been used to assess mangrove areas with good results (Green et al., 1998), whereby data from LANDSAT and SPOT are by far the most commonly applied (Newton et al., 2009). Additionally, more recently, images from CBERS (China-Brazil Earth Resources Satellite), which are freely available, have been used in few studies of mangroves (e.g. Guimarães et al., 2010).

In the northeast of Brazil, the São Francisco River Estuary (SFRE) comprises a significant mangrove area, important for human populations, where shrimp farming has been pointed out as the main anthropogenic activity affecting the mangroves (e.g. Carvalho, 2004; Semensatto, 2004; Cunha and Holanda, 2006). This area is part of a State Environmental Protected Area (APA), a Conservation Unit of sustainable use. The "APA Litoral Norte", considered here, was created in 2004 and still does not have a Management Plan (Sergipe, 2004). This study aims to map land/use cover on the SFRE, using a GIS-based analysis of satellite images (CBERS-2B and SPOT-5) and *in situ* verifications (ground-truth), in order to assess anthropogenic activities on mangrove ecosystem. Based on the results, guidelines for a local Management Plan were pointed out. Simultaneously, it was also highlighted the potential of remote sensing as a tool to aid in the management, conservation and sustainable use of mangroves.

2. Material and methods

2.1. Study area

The São Francisco River is one of the most important Brazilian water resources and is considered the River of National Integration, draining seven states along its 2 863 km. The river basin (636 919 km^2) is divided in four sub-regions from its nascent to its estuary: high, medium, sub-medium and low São Francisco (ANA, 2005). The SFRE is located in the low sub-region, on the boundary of Sergipe and Alagoas States (10° 30′ 27″S, 36° 23′45″W) (Fig. 1), in the Northeast of Brazil. The study area corresponds to the southern part of the SFRE (State of Sergipe) (Fig. 1) and covers approximately 192.35 km^2 and is part of the municipalities of "Brejo Grande" and "Pacatuba". This area was selected for the study because it is the region where the mangrove forests are located in this estuary.

The climate in this region is tropical semi-humid with a mean annual temperature of 25 °C, showing two outstanding seasons: one rainy, between April and August, and another dry, between September and March (Medeiros, 2003). This is included in the Tropical Wet & Dry (Aw) Climate, according to the Köppen Climate Classification System. The area is subject to a mid tide amplitude (between 2 and 4 m) with semi-diurnal tides (two high tides and two low tides) (Semensatto, 2004).

The study area is characterized by a remarkable lack of infrastructure, such as paved roads, hospital, health centre, schools and commercial stores. The inhabitants are deprived population composed of native residents whose income and subsistence depends on agricultural activities, aquaculture and mainly fishery. A total of eight fishery villages are distributed on this area, characterized by artisanal fishery practices, using canoes and fishing methods as line, net and gathering of crabs and shellfishes (CEPENE, 2008).

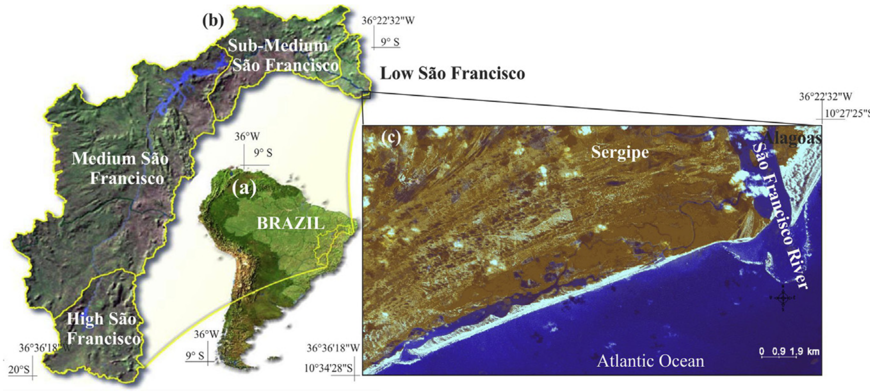

Fig. 1. (a) Map of South America and Brazil indicating the location of the São Francisco River basin (adapted from ANA, 2005). (b) The São Francisco River basin with its four divisions (adapted from ANA, 2005). (c) A close-up of the São Francisco River Estuary, the study area.

2.2. Satellite images and geoprocessing techniques

Imagery from CBERS-2B, SPOT-5 and LANDSAT-7 (Table 1) were processed using SPRING (Sistema de Processamento de Informações Georreferenciadas, Câmara et al., 1996) 5.0.4 edition, GIS software developed by INPE (National Institute for Space Research). CBERS (China-Brazil Earth Resources Satellite) images and SPRING software are freely available at URLs http://www.dgi.inpe.br/CDSR/ and http://www.dpi.inpe.br/spring/english/download.php, respectively. The LANDSAT image corresponded to the Orthorectified Landsat (ETM+) Thematic Mapper Mosaic and was freely acquired at https://zulu.ssc.nasa.gov/mrsid.

The orthorectified mosaic was used for geometric correction of the SPOT image which due to its high resolution was used to register the CBERS images. All images were enhanced with a linear contrast stretch and visually analysed. Based on the study of Green et al. (1998), the image processing techniques outlined below were applied.

Firstly, in order to produce an integrated product of CBERS-SPOT images, the data fusion technique (pansharpening) of RGB (Red-Blue-Green) → HIS (Hue-Intensity-Saturation) transformation was carried out using CBERS green, red and near-infrared wavelengths and then the reverse transformation HIS → RGB (Table 1), but replacing the "I" (intensity) image by the SPOT panchromatic band (Carper et al., 1990; Chavez et al., 1991; Crósta, 1992; Santos et al., 2010; INPE, 2011).

Secondly, in order to reduce the redundancy among images and increase the contrast of the image targets, principal component analyses (PCA) were performed with different data input (Table 1). After that, false colour composites (FCC) were produced using different layers (Table 1) and then enhanced with a linear contrast stretch.

Finally, a supervised classification using the maximum likelihood decision rule (MAXVER) was performed using CBERS near-infrared band and the first and second principal component (PC) of CBERS images (Table 1). The CBERS near-infrared band was chosen because it contains the vegetation spectral response. The third PC was not used as data input because the last component usually contains the image noise rather than spectral information (Crósta, 1992). Data from the CBERS-SPOT product were not used in the classification because the data fusion compromises the spectral information for quantitative techniques (Green et al., 1998).

A total of six classes were created: **mangrove** (areas of mangrove vegetation); **intertidal flats** (areas with herbaceous intertidal vegetation and/or exposed sediment located within mangroves); **sandy coastal vegetation and others** (*restinga* vegetation, dunes; sand spits, shoreline and small lagoons or flooded areas); **water** (sea, rivers, estuarine channels); **aquaculture** (ponds

Table 1
Characteristics of the original satellite images and processed images produced in the present study (PAN: panchromatic, R: red, G: green, B: blue, NIR: near-infrared, MIR: Mid-infrared, FCC: false colour composite, HIS: hue intensity saturation, PC: principal component, PCA: principal components analysis).

Original satellite images				
Sensor/satellite	Wavelength (μm)	Date	Path-Row	Spatial resolution (m)
HRG2/SPOT-5	PAN: 0.49–0.69	05/14/2008	731–371	2.5
CCD1/CBERS-2B	G: 0.52–0.59 R: 0.63–0.69 NIR: 0.77–0.89	05/14/2008	147–112	20
ETM+/LANDSAT-7	G: 0.52–0.60 NIR: 0.76–0.90 MIR: 2.08–2.35	2001	S.24–10	14.25

Processed images			
Name of processed layers	RS technique	Data input	Spatial resolution (m)
SPOT image	Linear contrast	SPOT PAN	2.5
CBERS composite	FCC and linear contrast	CBERS G, R, NIR	20
CBERS-SPOT product	RGB ↔ HIS transformation	SPOT PAN, CBERS G, R, NIR	2.5
First, second, third PC of CBERS-SPOT product	PCA	CBERS-SPOT product	2.5
Composite of CBERS-SPOT product	FCC and linear contrast	R, G and second PC of CBERS-SPOT product	2.5
First, second, third PCs of CBERS	PCA	CBERS G, R, NIR	20
Composite of CBERS PCs	FCC and linear contrast	First, second, third PCs CBERS	20
Supervised classification image	Supervised classification	CBERS NIR and first, second PC CBERS	20

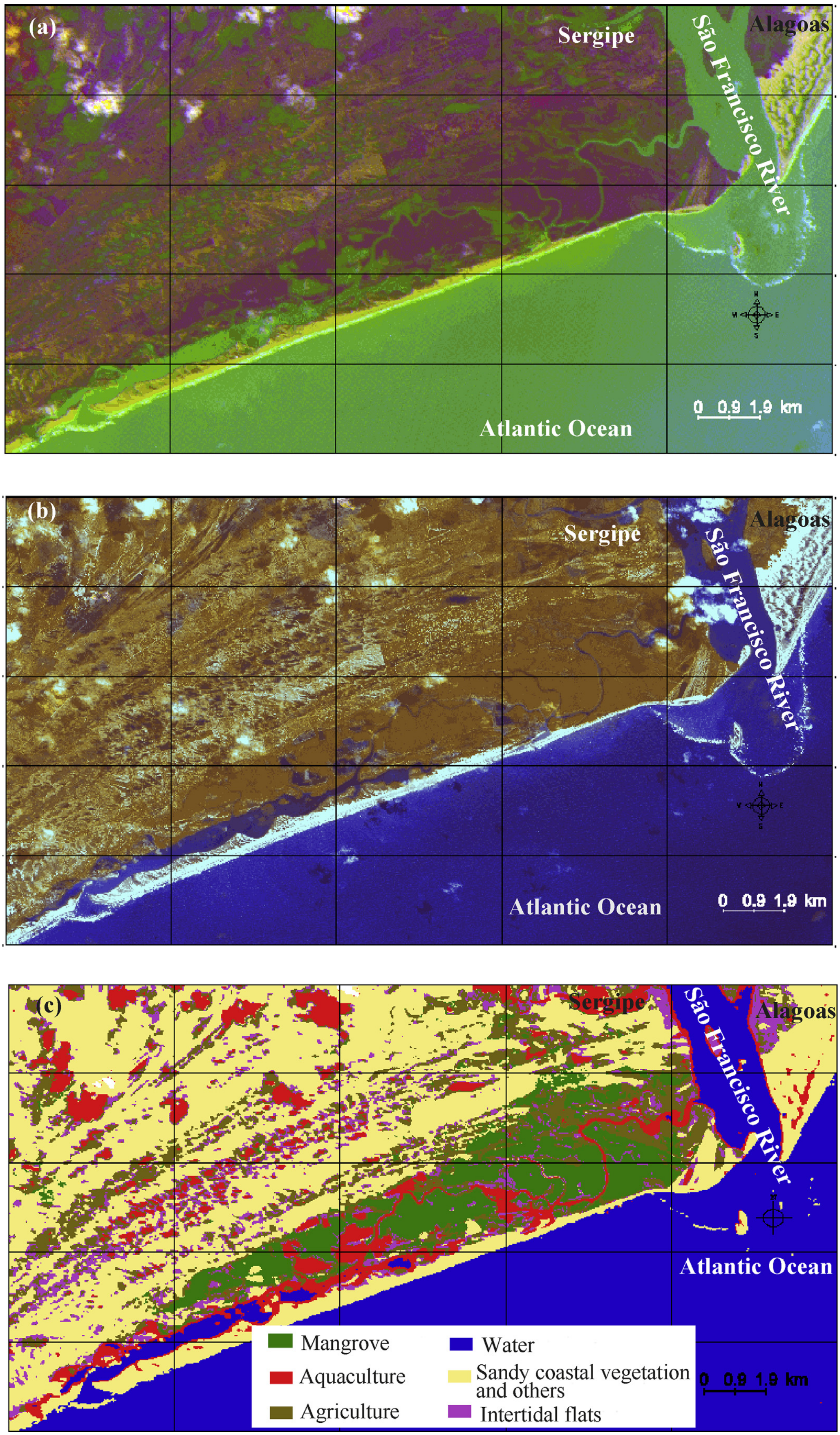

Fig. 2. Main results of image processing. (a) Composite of CBERS PCs (first PC at red channel, second PC at green channel and third PC at blue channel, where vegetation is highlighted in magenta, water in green and sandy sediments in yellow/white). (b) Composite of CBERS-SPOT product (second PC at red channel, green band at green channel and red band at blue channel, where vegetation is highlighted in red, water in blue and sandy sediments in white). (c) Supervised classification image. (PC: principal component). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

for shrimp and fish farming, as well as deforested areas adjacent to the ponds, which are part of aquaculture enterprises); and **agriculture** (rice and coconut plantations). The physiognomies presented in the class **sandy coastal vegetation and others** were grouped in one unique class because they occur as a natural matrix within *restinga* vegetation. *Restinga* is a typical Brazilian coastal vegetation found on sandy and nutrient-impoverished soils, frequently associated with a low-elevation plains characterized by the presence of beach ridges and lagoon systems (Flexor et al., 1984; Suguio and Tessler, 1984).

Training sites of each class were selected on the image and used to run the classification and determine the average performance, which correspond to the percentage of pixels correctly classified; and the average confusion, which correspond to the percentage of pixels misclassified, both calculated by SPRING based on the information of the training sites.

2.3. Land use and cover mapping and visual analysis

A land use/cover map of the study area was produced by the vector edition of polygons for each class in SPRING GIS. The vector edition was based on the supervised classification and visual interpretation of the false colour composite of CBERS-SPOT product, which showed the highest spatial resolution and contrast among the landscape classes. Line vectors for roads were also edited. Visual interpretation was based on colour, texture, shape, size, structure and position attributes (e.g. Avery and Berlin, 1992; Dahdouh-Guebas et al., 2006) with which an identification key was produced according to Dahdouh-Guebas et al. (2006). The shade attribute was not used because it was not visualized on the images. The final colour representation of the land use and cover classes was chosen based on the colour qualitative schemes for thematic maps (e.g. Brewer, 2005). The map accuracy was supported by digital colour aerial photographs from 2003 (Base, 2003) and ground-truth data from 2009.

The area of each land use and cover class and its percentage in relation to the total study area were determined. Moreover, in order to evaluate the relation between the extents of the anthropogenic lands in relation to the mangrove area, the ration in terms of percentage: **anthropogenic activity area/mangrove area × 100** was calculated. Supplementary materials such as aerial photographs from 1971 (Cruzeiro do Sul, 1971) and a cartographic map from 1986 (IBGE, 1986) were consulted to aid in the interpretation of the historic of the anthropogenic activities.

2.4. Field survey

Field missions (April–May 2009) were conducted in order to collect ground truth qualitative data about each class of land use/cover mapped. A total of 13 field stations were sampled during the field missions, based on expeditious sampling methods and rapid assessment (e.g. Filgueiras et al., 1994; Sayre et al., 2000; Breaux et al., 2005). In each field station a transect of 50 m was surveyed, along which qualitative data (up to an average of 1 m perpendicular from the transect) were recorded in a specific table and by ordinary photographs. The transects were surveyed using a measuring tape and recording the track, initial and final positions using a GPS (Global Positioning System, Garmin eTrex Venture HC). The specific table was previous elaborated and contained the information that was expected to be recorded in the field. Thus, as soon as the information was observed, it was marked on the table.

For the mangrove class it was recorded qualitative information about the vegetation, such as species composition: true, associate and non-mangrove species (according to Tomlinson, 1986), stature

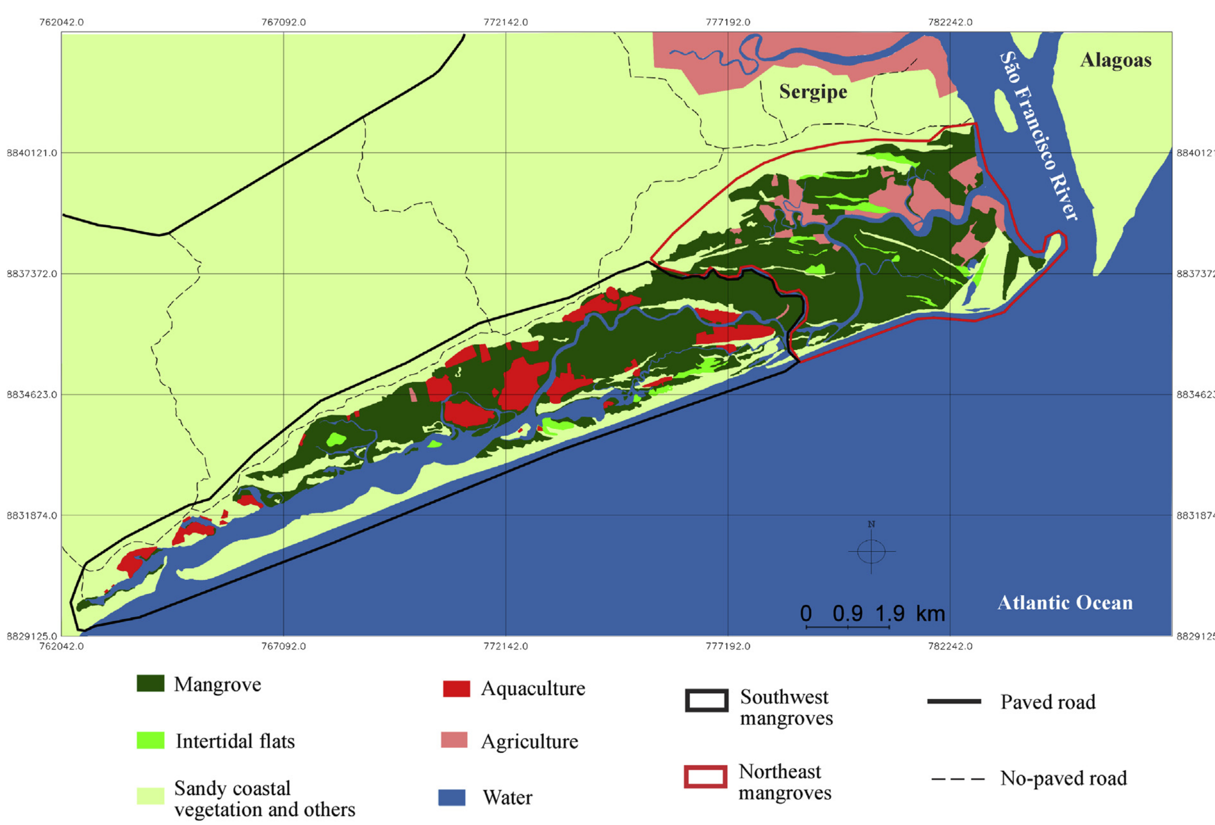

Fig. 3. Land use and cover map of study area in 2008, indicating the area of the southwest and northeast mangroves.

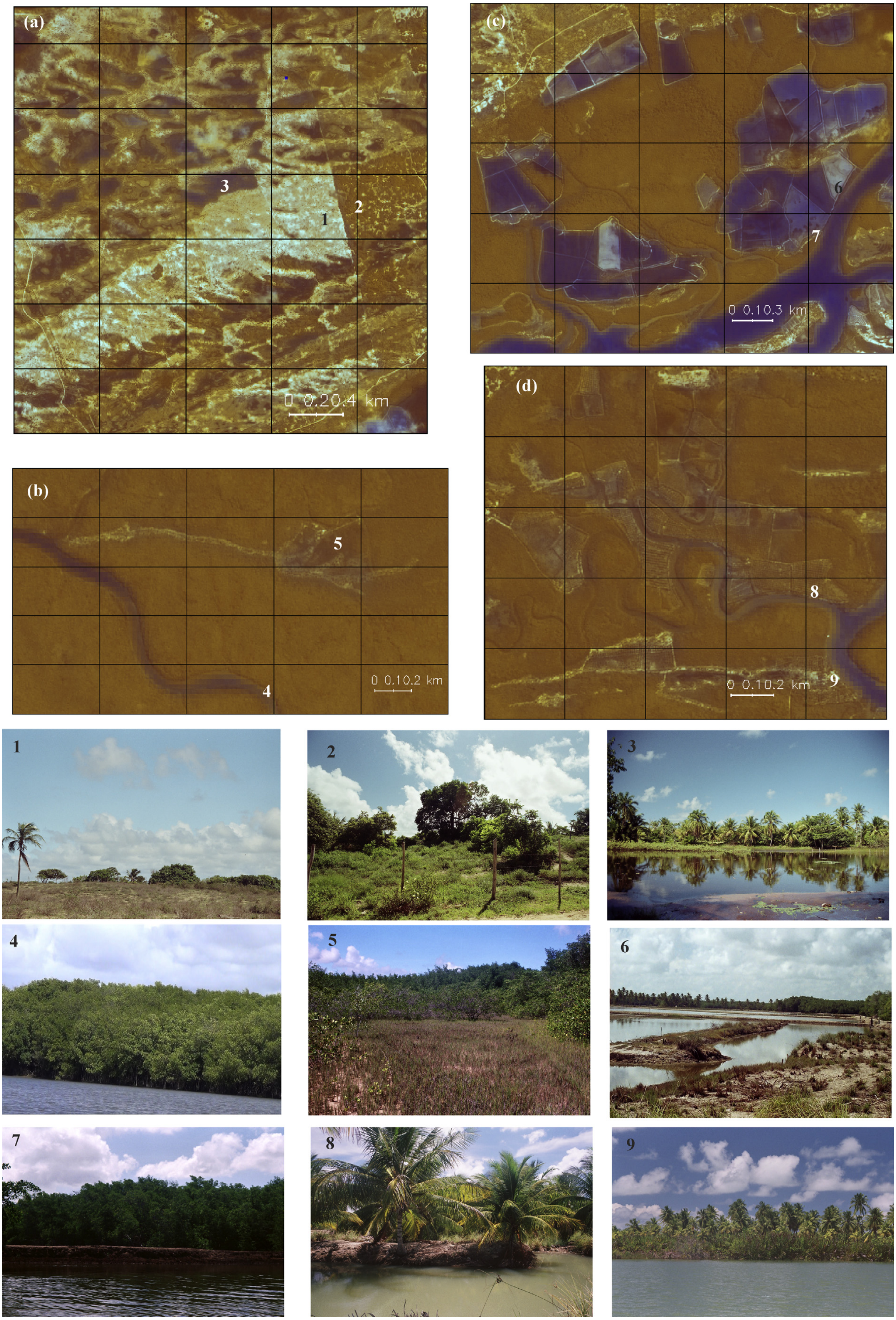
(a)
3
2
1
0 0.20.4 km
(b)
5
4
0 0.10.2 km
(c)
6
7
0 0.10.3 km
(d)
8
9
0 0.10.2 km
1
2
3
4
5
6
7
8
9

Table 2
Identification key of the classes of land use/cover types mapped in the study area using the CBERS-SPOT product.

Classes of land use/cover		Colour	Texture	Position	Shape	Size	Structure
Mangrove		Dark reddish	Medium to coarse grain	Along tidal estuarine channels parallel to the shoreline	Variable	Variable, but smaller-sized crowns than *restinga* woody vegetation	Patches of discontinuous and/or continuous canopy with crowns not visible separately
Intertidal flats		Light-reddish to blue-reddish	Plain and fine grain	Within mangrove vegetation	Variable	Small	Small patches with absence of trees forming a canopy
Sandy coastal vegetation and others	*Restinga* herbaceous vegetation	Light reddish	Fine grain	North portion of the study area (above mangroves)	Variable	Variable	Vegetation cover with absence of trees forming a canopy
	Restinga woody vegetation	Dark reddish	Coarse grain	North portion of the study area (above mangroves)	Circular canopy	Large-sized crowns	Patches of discontinuous canopy with separately visible crowns
	Sand, dunes and sand spits	White	Plain	North portion of the study area and along the shoreline	Variable	Variable	Patches and spits of sand arranged within vegetation or forming the shoreline
	Lagoons and flooded area	Bluish	Plain	North portion of the study area	Variable, mainly elliptic-shaped	Variable	Grouped or isolated small lagoons or flooded area
Aquaculture		Blue	Plain	Within southwest mangroves and near to tidal channels	Polygon-shaped and rectangular	Variable	Regular
Agriculture		Light reddish	Medium grain	Within mangroves and near to tidal channels	Polygon-shaped areas	Small-sized crowns	Crowns arranged in regular lines
Water		Blue	Plain	Variable	Variable	Variable	Variable

of vegetation: short (tree height ≤ 7 m), medium (height between 7 and 15 m) and tall (height ≥ 15 m), checking for the presence of gaps, seedlings and anthropogenic impact or interference, and colour/type of sediment. The identification of the mangrove species was made based on Schaeffer-Novelli and Cintrón (1986), Tomlinson (1986) and on the vernacular name of the species indicated by the field guide who is a native resident on the mangrove study area. Plants were identified in the field and when ambiguous by a *posteriori* comparison of photographs taken in the field with literature (Schaeffer-Novelli and Cintrón, 1986; Tomlinson, 1986).

For the others classes, general characteristics were recorded, such as vegetation habit (herbaceous, shrub, tree), type/change of human activity or interference, and colour/type of sediment. The geographical coordinates and paths of the transects were recorded on the GPS and, after the field work, they were transferred to MapSource software and then imported to SPRING GIS.

3. Results

3.1. Imagery analysis, anthropogenic activities and mangrove vegetation characterization

Fig. 2 shows the main remote sensing data produced in this study. The CBERS PC composite (Fig. 2a) presented high degree of colour contrast, but low spatial resolution (Table 1), limiting the visual analysis. The best data for visual discrimination was the CBERS-SPOT product (Fig. 2b) which showed the highest spatial resolution (Table 1). Despite the supervised classification (Fig. 2c) showed accurate result, with average performance of 96.6% and average confusion of 3.4%, some areas were not correctly classified, requiring visual edition. Therefore, to map the land use and cover types (Fig. 3) we combined the data of the classification and the visual interpretation of the CBERS-SPOT product (Figs. 2b and 4, Table 2). Most of the study area is occupied by cover types containing vegetation (Table 3, Fig. 3), such as sandy coastal vegetation and others (Fig. 4a), mangrove (Fig. 4b) and intertidal flats (Fig. 4b), while a smaller amount is occupied by land uses (Table 3, Fig. 3), such as aquaculture (Fig. 4c) and agriculture (Fig. 4d). From a total area of 13.6 km^2 of land uses, about 57% (7.8 km^2) occur within mangroves while 43% (5.86 km^2) occurs outside this vegetation. The land uses are spatially distributed within patches or fragments of mangrove vegetation (Figs. 3, 4c and 4d). An analysis of the relation between the land use and mangrove areas, shows that anthropogenic activities occupies roughly one quarter (24.4%) of the total mangrove area (Table 4).

Table 3
Area of the land use and cover classes and its percentage in relation to the total study area in 2008.

Classes	Area (km^2)	% To the total study area
Land cover classes		
Sandy coast vegetation and others	147.93	76.61%
Mangrove	30.48	15.79%
Intertidal flats	1.37	0.71%
Total	179.78	93.11%
Land use classes		
Aquaculture	4.46	2.31%
Agriculture	8.85	4.58%
Total	13.31	6.89%

Aquaculture is the anthropogenic activity occupying the largest area and percentage in relation to total mangrove extent, and corresponds to shrimp farming of the exotic species *Litopenaeus vannamei*. Aquaculture is spatially distributed within the southwest mangroves, making up for approximately 30% of its area (Fig. 3, Table 4). In the field, the southwest mangroves showed stands with heights ranging from short (height ≤ 7 m), medium (height between 7 m and 15 m) and tall (height ≥ 15 m) (Fig. 5a–c). It was

Fig. 4. Land use/cover classes of the study area showed in large scale in the CBERS-SPOT product (2.5 m of spatial resolution) and on field. (a) sandy coastal vegetation and others: 1 – *restinga* herbaceous vegetation, 2 – *restinga* woody vegetation, 3 – lagoon; (b) 4 – mangrove, 5 – intertidal flats; (c) 6 – aquaculture ponds, 7 – aquaculture pond beside a mangrove patch; (d) 8 – coconut cultivation on a dike, 9 – coconut cultivation behind a patch of *Acrostichum aureum*. (Photographs by Prof. Dr. Humberto Reis Matos and MSc. Luciana C.M. Santos).

Table 4
Evaluation of the extent of the anthropogenic uses in relation to the area of mangroves in 2008.

Land use type occurring within mangroves	Area of land use type	% Of land use in relation to mangrove total area	% Of land use in relation to southeast mangrove area	% Of land use in relation to northeast mangrove area
Aquaculture	4.46 km^2	14.63%	28.9%	0%
Agriculture	2.99 km^2	9.81%	0.38%	19.93%
Total	7.45 km^2	24.44%	–	–

recorded the occurrence of the typical mangrove species: *Rhizophora mangle* L., *Avicennia schaueriana* Stapf and Leechman ex Moldenke, *Laguncularia racemosa* (L.) Gaertn.f., and associated species: *Conocarpus erectus* L. and *Spartina* sp. Schreber. The presence of some stands with the largest structural development in the study area was registered, showing trees of *R. mangle* reaching heights up to 20 m. Moreover, narrow fringes of developed mangroves ahead of aquaculture areas (Fig. 5d) as well as fragments of

Fig. 5. Field characterization of the southwest mangroves: (a) short stature mangrove, (b) medium stature mangrove, (c) tall stature mangrove, (d) narrow fringe of tall mangrove ahead of an aquaculture pond (ellipse). Field characterization of the northeast mangroves: (e) *Scirpus* sp. and dense patches of *A. aureum* colonizing mangrove edges (f) *Acrostichum aureum* (red arrows) inside mangrove vegetation, (g) short stature mangrove and presence of *Montrichardia arborescens* (ellipse), (h) *Avicennia germinans*. (Photographs by Prof. Dr. Humberto Reis Matos and MSc. Luciana C.M. Santos).

mangrove forests beside them (Fig. 4c) were also observed in field. This can indicate that mature mangrove forests were converted to shrimp farming.

Agriculture use within mangroves corresponds to coconut cultivations which occupy a smaller area than aquaculture (Table 4) and are spatial distributed within the northeast mangroves (Fig. 3), making up of about 20% of this mangrove area (Table 4). In the field, this mangrove vegetation showed short (height < 7 m) to medium (height of 7 m–15 m) stature with the occurrence of the true species: *R. mangle*, *Avicennia schaueriana*, *A. germinans* (L.) Stearn and *Laguncularia racemosa* (Fig. 5g, h). Among the mangrove-associated species, it was registered *Conocarpus erectus*, *Spartina* sp. and *Acrostichum aureum*, the latter occurring as patches inside mangrove vegetation (Fig. 5f). Non-mangrove plant species such as the sedge *Eleocharis* sp. R.Br. and *Scirpus* sp. L. colonize the mangrove edges, along with patches of *A. aureum* (Fig. 5e). In addition, it was recorded the occurrence of typical species of freshwater environments such as *Annona glabra* L. and *Montrichardia arborescens* (L.) Schott scattered within short statute mangroves the in canal edges near to the mouth of the SFRE (Fig. 5g).

4. Discussion

4.1. Anthropogenic activities on the SFRE mangroves and guidelines for a local management plan

Although mangroves occupy a large area in relation to the entire study region, currently, these forests are pressured by shrimp farming and coconut cultivations. The historic of these human activities reveals different trends on their growth and pressure on the mangroves. In the 70's salt ponds and plantations of rice and coconut were the anthropogenic activities that occurred within the SFRE mangroves. In the 80's the salt ponds were converted to the cultivation of native fish species (ADEMA, 1984; Santos, 1997), and the rice plantations were abandoned and recovered by mangroves or replaced by coconut plantations which exist still now. Since ends of the 90's the areas used to fish cultivation were converted to shrimp farming (Carvalho, 2004; Semensatto, 2004). From 2004 to 2008 such activity showed an expressive growth of 70% in area (1.84 Km^2), and the number of shrimp farming firms roughly duplicated, recording 17 enterprises in 2004 and 36 in 2006 (Carvalho, 2004; CODISE, 2007; Barreto et al., 2009). This increase mainly occurred on areas occupied by mangroves (Barreto et al., 2009; Carvalho and Fontes, 2007). Moreover, due to the low technological level of production, shrimp farming offers few opportunities of jobs for the local populations and its production level (550 kg/ha/cycle, with about 2.5 cycles per year) is lower when compared with other areas in the State of Sergipe (Nunes, 2000; Carvalho, 2004). Despite this, the SFRE shows the third highest number of shrimp farming firms in relation to the 6 estuaries of the Sergipe State (CODISE, 2007). Additionally, a study by the State Government (CODISE, 2004) estimated more than 8.5 Km^2 as potential area for the development of such activity. Although these data indicate that shrimp farming is relevant in the SFRE, this activity seems to be the main anthropogenic pressure on the mangroves.

Since 2004 the SFRE is part of a State Protected Area of sustainable use, the "APA litoral norte", whose objectives include: the promotion of the socio-economic and sustainable development by activities that protect and conserve the ecosystems or essential processes to the biodiversity, the maintenance of ecological attributes, and the improvement of the life quality of the local population (Sergipe, 2004). This highlight the need to consider, in a Management Plan for this area, strategies to achieve such objects, specially for the sustainable development of shrimp farming which shows high extent, low contribution for the improvement of local livelihood and expressive growth that affect the mangrove forests.

Therefore, such management plan should emphasize the enforcement of the federal resolution n. 312/2002 (CONAMA, 2002b) and the state resolutions n. 12/02 and 12/04 (CECMA, 2002, 2004), which bring in principle all of the elements to guarantee the sustainability of shrimp farming (Jablonski and Filet, 2008). These resolutions forbids shrimp farming on mangroves and require several studies of ecological, environmental and socio-economic aspects for the environmental license. The Environmental Impact Study is only required for large-sized enterprises ($>$50 ha), or for those with smaller size when there is significant degradation of the environment, high density of enterprises and when it is located in a relevant environmental area.

The legalization of shrimp farming is an evident problem in the SFRE (Carvalho, 2004). For example, until 2007 there was not a census about the shrimp farming enterprises in this region and only one firm has requested license (Carvalho, 2004; Carvalho and Fontes, 2007; CODISE, 2007). Moreover, currently there are not available data about the number of shrimp farming firms that carried out the Environmental Impact Study. Here it was detected that various enterprises of shrimp farming occurs within the southwest mangroves of the SFRE (Fig. 3), accounting for about 30% its area (Table 4). Thus, in this region, due to an effect of high density of this activity, the Environmental Impact Study should also be mandatory for aquaculture enterprises with size smaller than 50 ha, as pointed out in the resolutions n. 312/2002 (CONAMA, 2002a, b) and n. 12/04 (CECMA, 2004).

The spatial distribution of shrimp farming within fragments of the SFRE mangroves might indicate their deforestation and conversion to such activity, and several studies have argued this (e.g. Carvalho, 2004; Semensatto, 2004; Cunha and Holanda, 2006; Barreto et al., 2009; Carvalho and Fontes, 2007). Aquaculture can cause several impacts when it is carried out without adequate management, such as immediate loss of mangrove forests for pond construction (Alongi, 2002; Primavera, 2006). Nevertheless, this impact can be avoid (e.g. Primavera, 2006; Guimarães et al., 2010) and the new strategies proposed during the last decade have proven that it is possible to reach a sustainable aquaculture (Martinez-Porchas and Martinez-Cordova, 2012). Additionally, certification processes can be followed to assure the sustainability of aquaculture, which are performed by the International Standards Organization (ISO), the WTO Technical Barriers to Trade (TBT), the FAO Guidelines for the Ecolabelling of Fish and Fishery Products from Marine Capture Fisheries, the Network of Aquaculture Centres in Asia-Pacific (NACA), the Global Aquaculture Alliance (Best Aquaculture Practices, BAP) and others (Corsin et al., 2007; Martinez-Porchas and Martinez-Cordova, 2012).

In mangrove areas sustainable aquaculture is dependent on the extent of mangrove conversion into ponds (Bergquist, 2007). In this view, we consider sustainable aquaculture practices in mangrove areas those that are developed in small-scale, preferably use native species, involve local communities in management, profit and consider their socio-economic welfare, use technologies for effluent treatment and to avoid/mitigate environmental impacts, maintain areas of mangrove for conservation/restoration and mainly do not involve deforestation/conversion of mangrove forests (e.g. Primavera, 2006; Bergquist, 2007; Guimarães et al., 2010; Haque et al., 2009; Martinez-Porchas and Martinez-Cordova, 2012).

There are sustainable manners to construct aquaculture ponds that do not depend upon the conversion of mangrove areas (Guimarães et al., 2010). Mangrove-friendly aquaculture considers that aquaculture can be developed in mangrove sites without their deforestation. For example, species of bivalves or fish in cages can be grown in mangrove waterways, in small-scale, family-based operations and can be adopted in mangrove conservation and restoration sites (Primavera, 2006).

The study area shows potential for mangrove-friendly aquaculture, such as for cultivation of the mangrove oyster *Crassostrea* sp. (*personal observation,* e.g. Moura and Meira, 2002) and native fish species, which were traditionally cultivated by the local communities (e.g. ADEMA, 1984; Santos, 1997; Dos Santos *personal comunication*[1]). In this view, a management plan should support the creation and development of cooperatives of local residents for the execution and managing of these practices. The plan should ensure that technical and financial subsidies should be provided by various institutions, including marketing organizations, university-based research institutes, and government agencies (e.g. Haque et al., 2009). For an ecological and social sustainable aquaculture, a holistic approach requiring the participation of other stakeholders including fishers and local communities is essential (Primavera, 2006).

Others strategies and technologies to achieve a sustainable aquaculture includes: closed and semi-closed water systems, systems with low or zero water exchange, recirculation systems, natural feed, polyculture and integrated multitrofic aquaculture (IMTA) (Balasubramanian et al., 2005; Primavera, 2006; Bergquist, 2007; Kuhn et al., 2008; Martinez-Porchas et al., 2010; Martinez-Porchas and Martinez-Cordova, 2012). Therefore, for the introduction of new aquaculture enterprises in the study site, a management plan should prioritizes the implementation of those with such features. Additionally, this plan should support the accomplishment of workshops to improve the current aquaculture practices to more sustainable alternatives.

Coconut cultivation is the other current anthropogenic activity occurring within the northeast mangroves, and it is an important socio-economic activity for the region, serving as source of income for the local population (SEPLAN, 2010). In this view, it is important to highlight that there are practices which integrates aquaculture with agriculture. The integration of these activities is relatively more diversified and reliable livelihood, in which production costs can be reduced further by using the by-products and other services from these activities (e.g. erosion control, filtration, making feed, pond sludge) (Hilbrands and Yzerman, 1998; Primavera, 2006; Bergquist, 2007). Considering this, a management plan should offer strategies to support the local people to develop the integration of coconut cultivations with aquaculture. In case of expansion of coconut cultivation, sand spits (without *restinga* vegetation) and sandy land areas in or near the villages, might be alternatives areas for coconut cultivation, instead of areas with mature mangrove forests.

4.2. Remote sensing and GIS: potential tools to aid in mangrove management

The detection and extraction of data about the spatial distribution and extent of coastal ecosystems and anthropogenic activities are essential information for the elaboration of management plans. The use of remote sensing techniques to map land/use cover in coastal areas provides this type of information, as demonstrated in this study.

Here, the fusion of CBERS and SPOT images produced an efficient data for a detailed detection of the coastal ecosystems and anthropogenic activities, and the integration of visual discrimination and automated methods (supervised classification) was the most efficient approach to map the land use/cover. Within the literature, there is a tremendous emphasis on automated methods (Brandtberg and Walter, 1998; Kadmon and Harari-Kremer, 1999), despite the fact that in many cases human eye interpretation of images is found to be one of the best way of obtaining information (Dahdouh-Guebas et al., 2006). The findings of the present study highlight the importance of integrating both types of methods.

Remote sensing GIS-based studies provide a synoptic view, which is not possible to obtain by *in-situ*-based studies. Therefore, that analysis can aid in practical issues of coastal management, such as monitoring, at a distance, of the fulfilment of environmental laws in coastal areas. Many studies have shown the importance of remote sensing tools, specially, satellite images for the multi-temporal monitoring of mangrove forests and anthropogenic activities (e.g. Heuman, 2011; Kuenzer et al., 2011; Santos et al., 2012). However, the expensive prices to be paid for commercial satellite imagery and GIS software may constitute a limitation for developing countries (Dahdouh-Guebas et al., 2006). This highlights the importance of freely available geospatial tools, such as CBERS images and SPRING GIS, which can be used for such purposes and, consequently, producing information to aid in decision make and elaboration of management plans for coastal conservation.

5. Conclusions

We concluded that the remote sensing approach used in this study, such as the CBERS-SPOT product and the integration of visual and semi-automated methods, was an efficient and cost-effective method for the analysis of man-driven pressures on the mangrove vegetation. This approach generated data and information necessary to establish a number of guidelines for the elaboration of a local management plan, and can be applied in other coastal areas with similar needs, particularly for those where shrimp farming is an activity that affects mangroves.

Based on these data, we found that shrimp farming is the main anthropogenic pressure on the SFRE mangroves. Therefore, we suggest that a Management Plan for the SFRE should considers: the implementation of sustainable aquaculture practices such as small-scale enterprises that preferably use native species, involve local communities in management, profit and consider their socio-economic welfare, use technologies for effluent treatment to avoid/mitigate environmental impacts, maintain areas of mangrove for conservation/restoration and mainly do not involve deforestation/conversion of mangrove forests; strategies for the compliance of the Brazilian laws regarding shrimp farming license and operation; support the creation of local resident cooperatives for the execution of sustainable aquaculture; and integration of aquaculture with agriculture.

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[1] Rafael dos Santos. Native resident of the study area and local agent of TAMAR (Sea Turtles project), who acted as a guide and boatman of this study fieldwork. Information provided on 18/04/2009.

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