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ORIGINAL ARTICLE

Spatial database modeling for mangrove forests mapping; example of two estuarine systems in Brazil

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Abstract This work considers mangrove cover changes in two subtropical estuaries in the southeastern coast of Brazil: Cananéia-Iguape Coastal System and Santos Estuarine System. A sequence of Landsat images from 1985 to 2014 from both areas was segmented, classified and analyzed in order to develop a systematic GIS approach for *identifying and characterizing* mangrove fragments in such estuaries and how they change over time. The main goal of our work is to propose a *unified hierarchical spatial database model in a* GIS framework *developed* to incorporate different types of spatial information such as spectral (e.g. vegetation indices), spatial (e.g. fragmentation indices) and temporal (e.g. change detection) at different scales. The examples analyzed showed that changes and fluctuations in mangrove habitats could be identified and characterized *revealing* potential tools for handling and analyzing data focused on *environmental monitoring* and the coastal resource protection and conservation.

Keywords Remote sensing · GIS · Time change detection · Subtropical wetland · Coastal zone management · Conservation · Geospatial database

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Introduction

Mangroves are transitional formations occurring along tropical and subtropical coastline regions. These coastal ecosystems are located in wetland plains and are subject to a semi-diurnal tidal regime. They consist of woody plant species (angiosperms), and micro-and macro-algae (cryptogams) adapted to salinity fluctuation and are predominantly in pelitic sediments, with low levels of oxygen. According to recent studies, about one-third of mangrove forests have been lost within the past 50 years worldwide primarily due to removal by human activities (Alongi 2002, Liu et al. 2008, Rebelo and Finlayson 2008; Spalding et al. 2010, Doughty et al. 2015).

Remote sensing has been widely proven to be essential to easily obtaining quantitative and qualitative information about coastal wetlands, *specifically, saltmarshes and mangroves.* Although several techniques have been developed to characterize coastal wetlands distribution, in particular mangroves, there is no one specific method that meets all demands of monitoring and mapping mangrove ecosystems (Cintrón and Schaeffer-Novelli 1984; Green et al. 1998; Reddy et al. 2007; Giri and Muhlhausen 2008; Paling et al. 2008; Kuenzer et al. 2011; Myint et al. 2014; Aziz et al. 2015).

Many algorithms have been developed for remote estimation of biophysical properties of vegetation, in terms of combinations of spectral bands, in particular the mathematical combination of visible and near-infrared reflectance bands, and in the form of spectral vegetation indices. Such techniques, especially when combined with land use data, are increasingly important to studies that must differentiate between natural variation in ecosystem function and variation arising from human activities, such as habitat conversion (Viña et al. 2011; Kerr and Ostrovsky 2003; Díaz and Blackburn 2003; Vo et al. 2013; Ibharim et al.

2015; Son et al. 2015). However, studies have shown that *considerable variation* of values of vegetation indices in mangroves can be found *depending upon the background soil response* (i.e. if they were growing over white sand, or if dark organic detritus covered the sediment) or physical condition of the area during the imagining (i.e. tidal cycle, suspended sediment concentrations, moisture content, Díaz and Blackburn 2003; Green et al. 1997). Thus, no single vegetation index can be expected to completely summarize the information in a multidimensional spectral data space. Wallace and Campbell 1989 and Coppin et al. 2004 aptly stated that adequate indices can be found for different purposes and that indices derived for one analysis may be inappropriate in another context.

In addition, the use of geographic information systems (GIS) to identify and model environmental features in wetlands have also expanded to handle large quantities of data from different sources aside from *spectral information*. Examples of Geoprocessing techinques applied to mangrove studies can be found in Cohen et al. Cohen and Lara 2003, Krause et al. 2004, Zharikov et al. 2005, Luong et al. 2015 and yet, a multiscale analysis approach remains challenging for environmental coastal studies. Schaeffer-Novelli et al. 2000, Rovai et al. 2016 proposed that mangrove analysis can be *organized into hiearchica* levels composed of patches, stands, settings, coastal segments and large marine ecosystems. Each of these describes an organization that has evolved to facilitate energy dissipation at its relevant scale, and can be related to a geographic unit, and one of the challenges of *implementing* GIS projects in a mangrove ecosystem is in *incorporating such scale semantics into an organized spatial database model. Several environmental spatial models have been developed to assess landscape* structural quantification such as fragmentation indices and spatial analyses (for details, see Gustafson 1998; Metzger and Décamps 1997; Southworth et al. 2002; Dewan et al. 2012; among others) but most of the approaches have been developed for the landscape level and not applied to a specific class or habitat.

In the current study we combine two different approaches to evaluate the evolution of two subtropical estuarine areas with different levels of anthropogenic pressure: shape analysis (based on landscape metrics) and Spectral analysis (based on values of vegetation indices). As such, the methods allowed an objective evaluation of the wetlands conditions in time and provide a tool to facilitate monitoring and managing of coastal areas.

We have chosen two estuarine areas, on Brazil's southeast coastline (Fig. 1), with similar structure, microtidal regime and dimension located approximately 80 km apart (north–south) but with different levels of human activity and degradation.

The Cananéia-Iguape coastal system, located between 24°40′S and 25°20′S (Fig. 1a), consists of a complex of lagoon channels, and is part of a UNESCO World Heritage site, with criteria (vii)(ix)(x), since 1999. It can be divided into two sectors: northern and southern, based on geomorphology and environmental conditions. In the northern sector, important environmental changes occurred over the last 150 years due to the opening of an artificial channel. This artificial channel (Valo Grande), which connects the Ribeira River to the coastal system, produced significant modifications in salinity, depositional patterns and input of heavy metals resulting from lead mining by-product effluent dumped into the system, although these ceased in 1995 (Mahiques et al. 2009; Tessler et al. 1990). The southern sector, which is less influenced by the low salinity of the artificial channel, is considered the best conserved mangrove area along the coast of the State of São Paulo (Cunha-Lignon et al. 2011). In this sector, the mangrove forests located in accretion areas were always associated with smooth cordgrass *Spartina alterniflora*, which helps the fixation and colonization of mangrove seedlings and saplings (Cunha-Lignon et al. 2009). The current study focused on the Cananéia region, located on the southern sector of this coastal system.

The Santos Estuary System, located between 24°50′S and 23°45′S (Fig. 1b), is home to the biggest port of Latin America (Santos Port) and a petrochemical industrial complex (Cubatão Industrial Complex), also known in the 1980s as "Death Valley" because of its outrageous carcinogenic pollution rates. It was estimated that the region lost about sixty percent of its mangrove forests mainly due to harboring and industrial activities. According to Cunha-Lignon et al. 2009, the expansion of the urban area, the construction of highways and port expansions have reduced and fragmented extensive areas of mangrove vegetation in the Santos Estuary System. Menghini et al. (2011) suggested long-term monitoring studies on impacted mangroves to develop effective tools to help better understand the response of systems exposed to anthropogenic induced stressors in the Baixada Santista region. The Santos Estuarine system (S-ES) presents substantial anthropogenic pressure from industrial activities, urban sewage and polluted solid wastes disposal (Hortellani et al. 2005). Currently, there are nearly 400,000 people living in this area, but the cities of Santos, Cubatão and S. Vicente and adjoining regions account for 1,000,000 inhabitants (almost doubled in the vacation period).

Methods: the geodatabase concept

Land use/cover change trends in the area were determined by analyzing a series of satellite images (Landsat-5 TM) with approximately 2–3 year intervals (years of 1985, 1989, 1992, 1995, 1999, 2002, 2005, 2008, 2012 and 2014

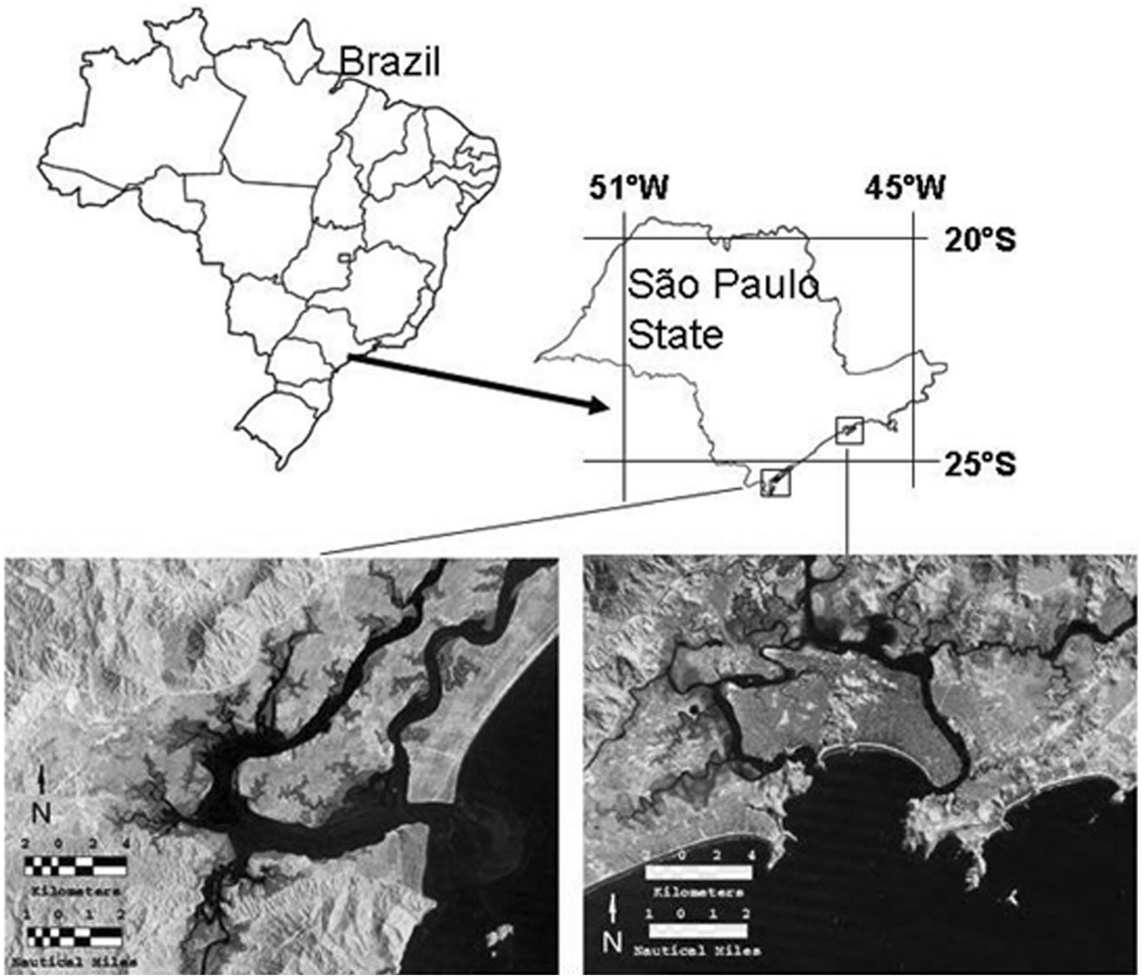


Fig. 1 Study site **a** the Cananéia region, in the Cananéia-Iguape Coastal System; **b** the Santos Estuarine System

for Santos Region and 1992, 1994, 1999, 2005, 2008 2010 and 2014 for Cananéia region). Deriving accurate information on natural ecosystem change is the primary challenge in standard remote sensing: maximization of the signal-to-noise ratio and pre-processing of multi-data imagery is a much more daunting task than in a single-date case (Coppin et al. 2004). It commonly comprises a series of sequential operations, including (but not necessarily in this order) calibration to radiance or at-satellite reflectance, atmospheric correction or normalization, image registration, geometric correction, mosaicking, sub-setting and masking (e.g. for clouds, water, irrelevant features). Standard techniques were used to pre-process the Landsat TM data. The scenes were georeferenced to ortho-rectified GeoCover images using a well-distributed set of ground control points achieving less than one-half pixel root mean square (RMS) error. The atmospheric correction was made using a dark Subtraction Method (Chavez 1996).

The mangrove areas were selected using object-oriented classification for each scene. Object-based classification (OBC) can be an alternative to the traditional pixel based methods imposed by conventional classifiers, in particular to overcome the problem and salt-and-pepper effect, it can be useful to analyze groups of contiguous areas as objects as classification units reducing local spectral variation and noise caused by crown textures, gaps, and shadows (Yu et al. 2006). The first step to perform an OBC involves segmenting the images based on a bottom-up region merging process, in which the smallest object contains one pixel. In subsequent steps, objects are merged into larger ones based on specific spectral parameters, which define the growth in heterogeneity between adjacent image objects (Laliberte et al. 2004; Benz et al. 2004). Segmentation was followed by the classification process where the Bhattacharya distance method was used with the acceptance threshold of 99 % (see details in Thomas et al. 1987). High-resolution images (Quickbird Images and aero photographs) were used to calibrate and evaluate the classification method's efficacy and accuracy. All mangrove fragments on each date from the Cananéia and Santos

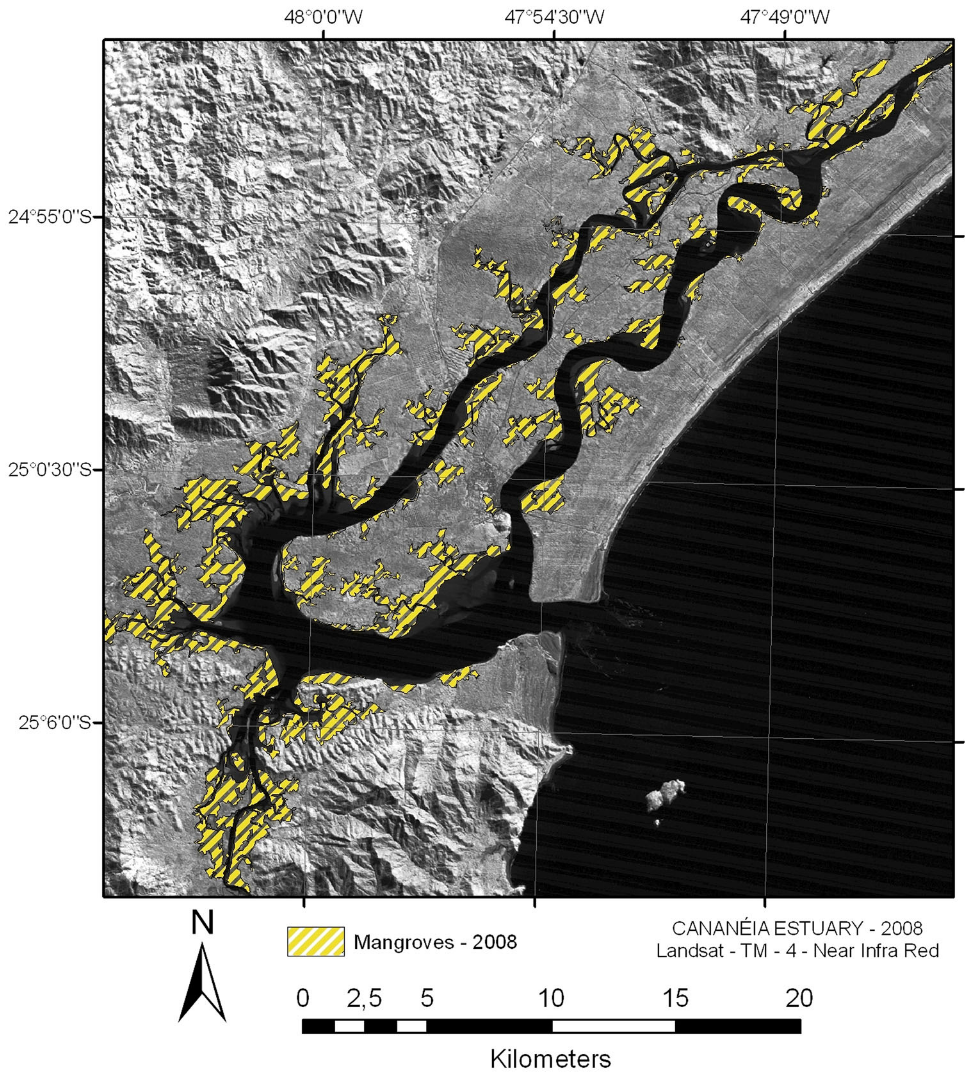


Fig. 2 Mangrove patches distribution (image of 2008)—Cananeia Estuary

estuary were selected and vectorized as individual polygons and identified with an ID code into the Geodatabase.

Despite that the databases were created for all sets of mangrove fragments in each estuarine zone, not all features were considered in this analysis. Many studies have provided insights into the effect of spatial resolution on landscape indices but, as mentioned by Saura 2004 and Frazier 2016 it is not yet fully understood how fragmentation indices are affected by the original image resolution. In this work we have restricted the analysis to larger fragments (bigger than 30,000 m^2, which corresponds to approximately 92 % of the mangrove area in the case of the Santos estuary and 89 % of Cananéia). This restriction was adopted since small fragments have the potential of amplifying positional errors associated with geometric shifts between images and enhance the pixel effect on the fragments (Goodchild 2004; Wickham and Rhtters 1995). This boundary has been chosen since we have observed that the pixel effect (i.e. the influence of the "step-like" influence of the pixels) in *fragments smaller than aprox.* 30,000 m^2. We have, therefore, considered this size as the limit boundary of analysis mangrove patterns with at least 25 (e.g. 5 × 5) original TM pixels. Figures 2 and 3 show the Mangroves polygon distribution in the Cananéia and Santos study sites.

Metric and fragmentation analysis using landscape indices was performed using the *Patch Analyst* extension for ArcGIS, in order to characterize quantitative shape metric parameters for each fragment (or patch units according to Schaeffer-Novelli et al. 2000). All numerical results from the analysis (i.e. mean shape index, area, perimeter, fractal dimension, among others) were compiled into the created spatial database. Both estuaries were also analyzed as a whole Landscape using class metric statistics (or "coastal segments" according) such as "patch density", "number of patches", "mean area", and "mean

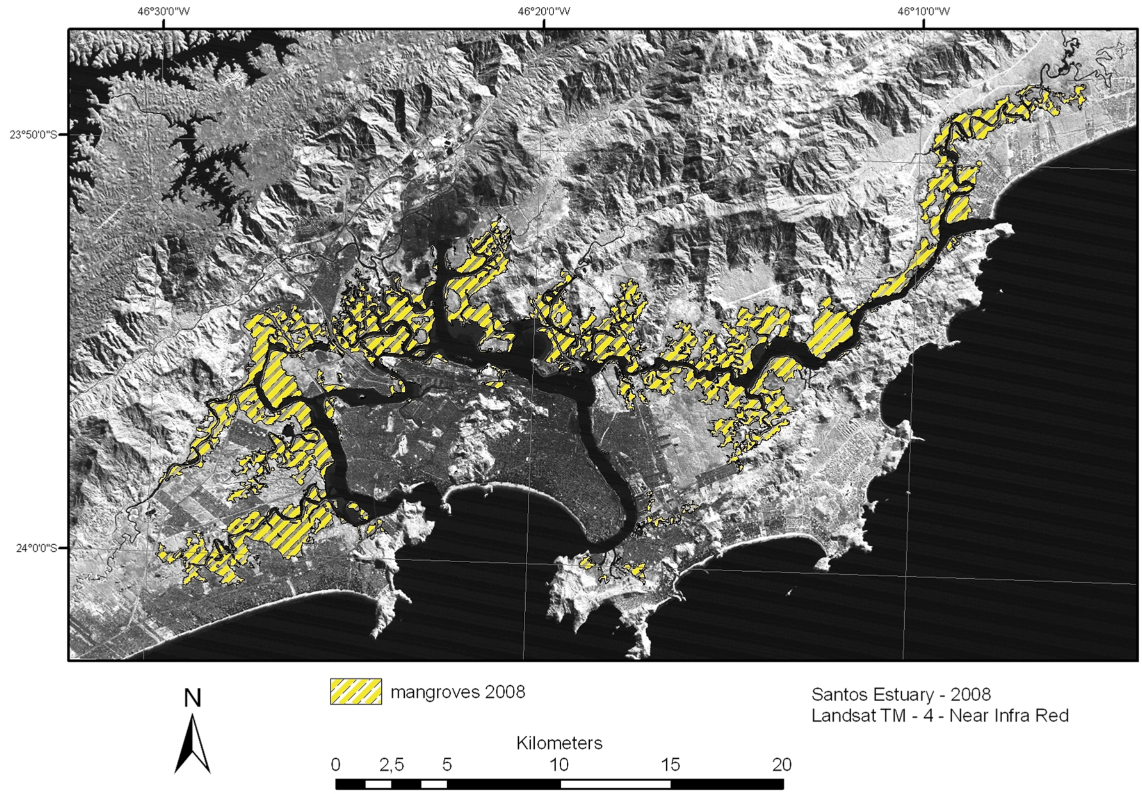


Fig. 3 Mangrove patches distribution (image of 2008)—Santos Estuary

perimeter". Details of the method can be found in Ritters et al. 1995 and Fahrig 2003.

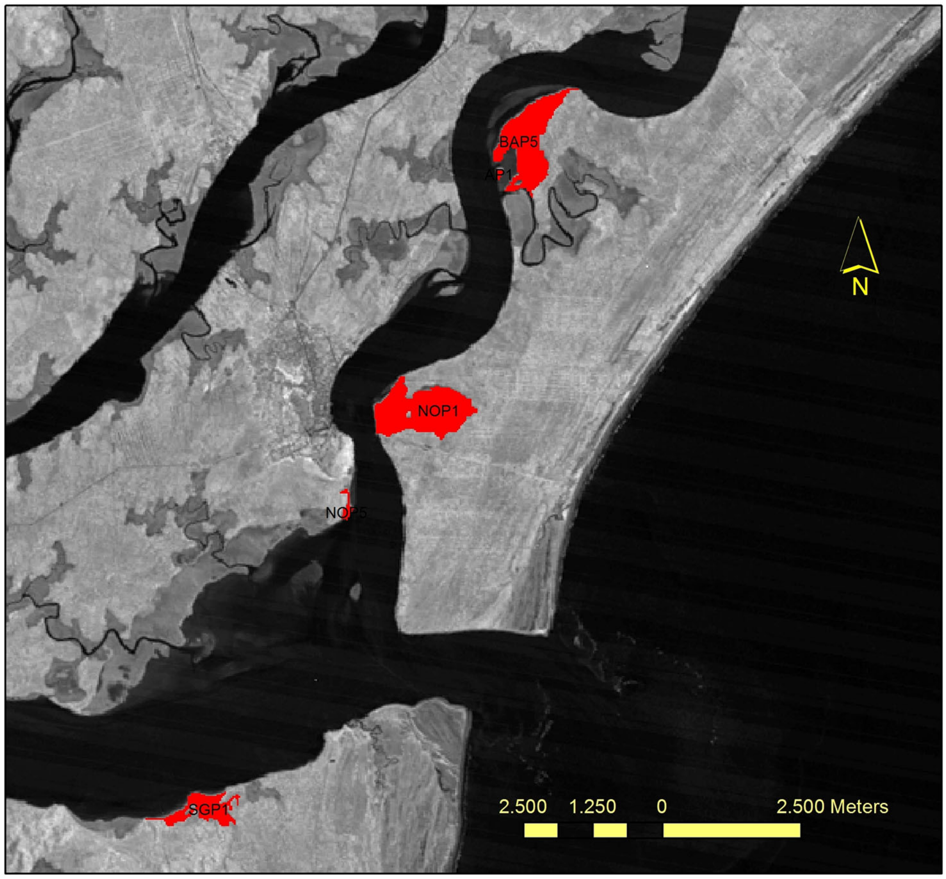
Quantitative levels of spectral information *measurements* were *taken for each fragment (mean, minimum, maximum, standard deviation)* and correlated with the metric parameters previously described. The mangrove patch polygons were used as restriction targets in "zonal" analysis where parameters such as the Normalized Vegetation Indice (NDVI) and "Tasseled Cap" *Greenness*, *Brightness* and *Wetness* values where obtained from the original images (details in Zhang and Qingjiu 2013). Additional spectral information derived from the Landsat images such as band intensity levels and classification accuracy indices were also extracted for regional zonal analyses.

Complementary topological information about the distances for specific features has also been considered. We determined factors such as "Anthropic Influences Areas (AIA)", inlets and main channel as chosen features for establishing distances from the patches. The AIAs were characterized as polygons representing a concentration of urban/industrial areas derived from the classified Landsat images. The inlet areas were represented as points at the central part of the inlet (or inlets in the case of the Santos Region). The Main channels were considered the central part of the larger estuarine channels that capture the adjacent drainage network. The distance measurements were recorded considering the minimum distance between the mangrove fragments to the selected features (AIA, inlets or channels).

In specific areas, point and profile field measurements were taken and related to the geodatabases as derived tables into the corresponding patch (Cunha-Lignon et al. 2009). We collected data on mean tree diameter; mean height and standard deviation (stdev); density; and basal area (BA). Due to the complexity required for elaborating fieldwork and data collection, only a fraction of all fragments included all this data (Fig. 4).

Figure 5 shows a schematic representation of the database building methodology. In part of the attribute database of the evaluation of mangrove fragments, the columns represent attributes of pattern form (e.g. area, perimeter), landscape indices (e.g. main shape index (MSI), fractal dimensions), spectral indices (e.g. NDVI) and distances (to inlet and AIA). One geodatabase layer was generated for each image analyzed (tables).

The relationship of the parameters organized into the geodatabase on each area/date can be analyzed in a very straightforward way (i.e. multi parametric statistics). Change parameter values in time (time change detection), however, indicate the dynamics of the objects and brings a considerable challenge to maintain data integrity. As a new mangrove patch could appear, disappear, merge or split,



Shape *	ID	FID	id1	Plot	MTD	MH	STDEV	(%) RH	(%) LG	(%) AV	BAS>10	DEN	BAS 2,5 - 10
Polygon	13	120	139	AP1	1,0	1,	0,16	---	99,1	0,90	---	1600	---
Polygon	14	125	145	BAP5	6,3	7,	2,25	5,58	19,61	74,80	11,54	5733	6,25
Polygon	20	179	266	NOP	1,6	1,	0,56	3,90	96,1	---	---	8555	4,86
Polygon	21	190	218	NOP	6,2	3,	3,37	84,39	0,24	15,37	17,51	7200	2,05
Polygon	27	232	271	SGP1	2,2	2,	0,75	44,91	40,37	14,71	---	6720	14,77

Fig. 4 Table of measured structural parameters: mean tree diameter; mean height and standard deviation (stdev); density; and basal area (BA) contribution. Study sites and abreviations: Baguaçu (BA); Nóbrega (NO) and Sítio Grande (SG). Rh *Rhizophora mangle*, Lg *Laguncularia racemosa*, Av *Avicennia schaueriana*

new Patch IDs should be assigned. This process would carry over from for each image for each study area. In situations where patches merged, the old Patch IDs would be retired and a new Patch ID grouping or sub grouping would be referenced to the new consolidated object.

Once each patch feature Id was correctly organized into the multitemporal database, any parameter could be analyzed and compared to determine time changes in any spatial or spectral atributes. Figure 4 shows examples of such object changes with their relation with geodatabase parameters and geoprocessing method (Fig. 6).

Discussion and conclusion

The combined analysis of landscape metrics with spectral information offers a meaningful approach in the characterization of environmental settings and changes in mangroves and coastal wetlands. While most of the methods in the time-change detection rely on the single factor analysis (spatial, topological or spectral), the combination of all apporaches provided new interpretation possibilities. The analysis of such combined methods allows us to characterize a different dynamic of changes in mangroves in the Cananéia and Santos Region. Figure 7 shows the spatialization of the changes in mangrove formation between 1985 and 2010.

The results indicate that most of the shape variability of mangroves in the Cananéia Region is related to changes in patch form and complexity related to local hydrodynamic processes into the estuary (Fig. 2a). Pr*evious work in this area described the intensity of hydrodynamic* forcing near the inlet and in other parts of the lagoon system (Conti et al. 2012; Cunha-Lignon et al. 2011), which could lead to an erosion and accretion process and consequently changes in mangrove patches, particularly in marginal areas, near the main channels in particular on curved shorelines (scattered over the estuary). In the Santos region (Fig. 2b), significant changes were verified in mangrove fragments but, at the opposite end of the Cananéia region, these

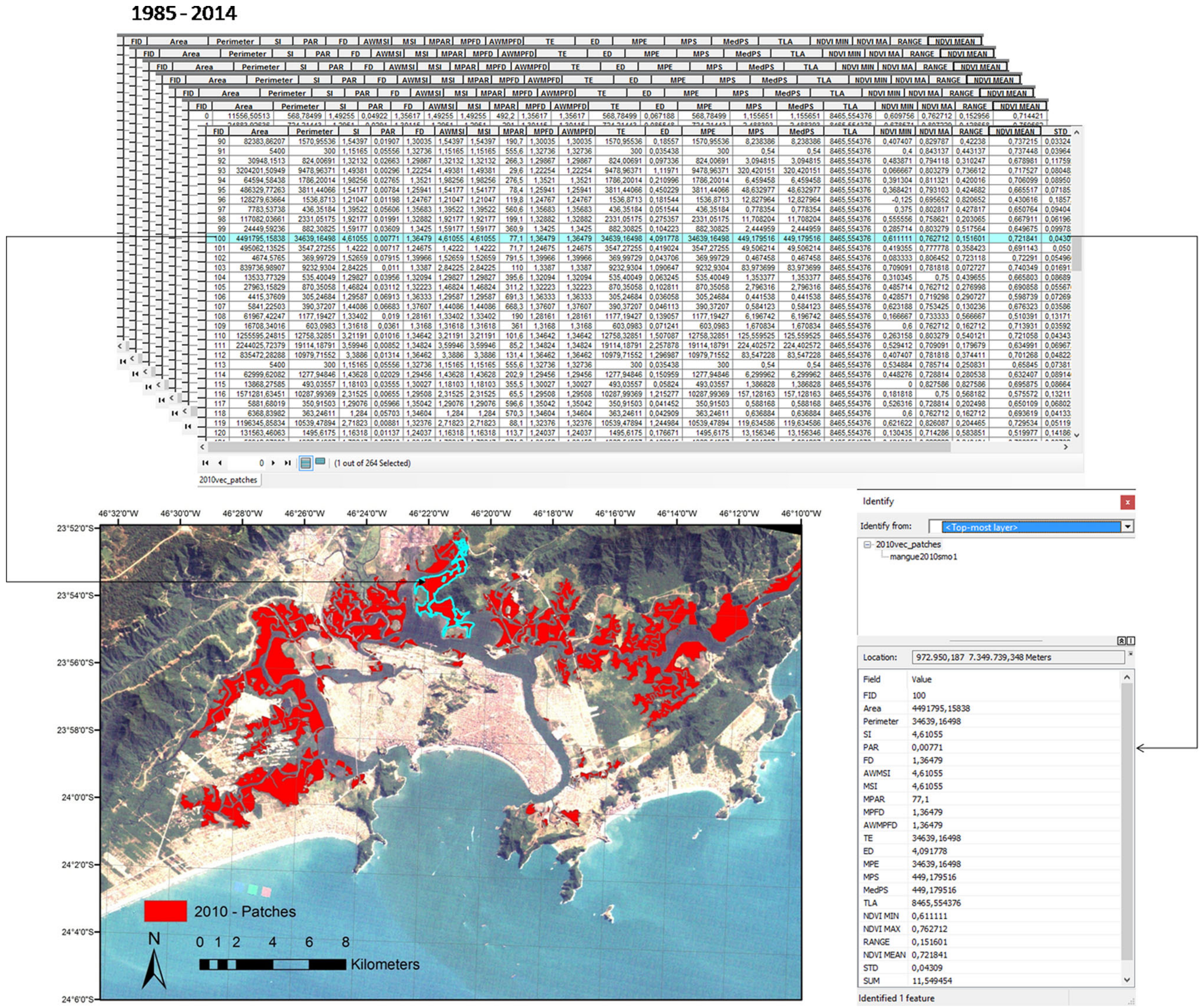
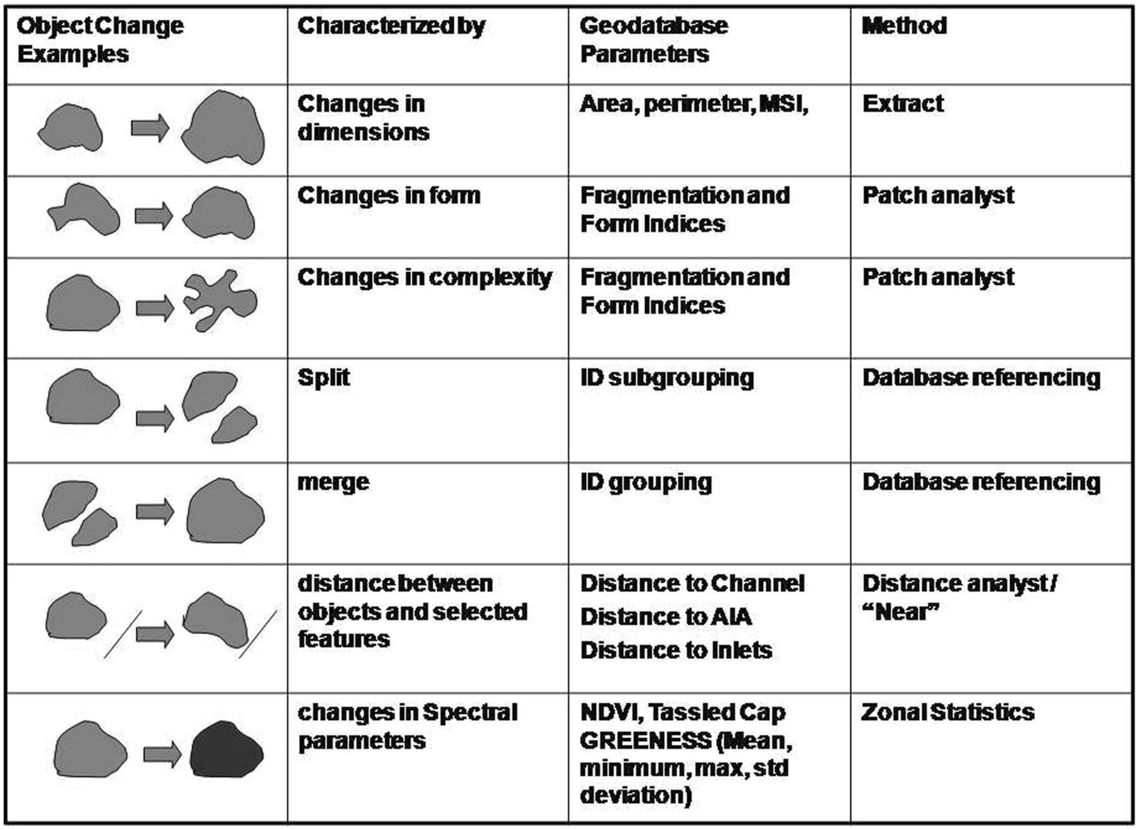


Fig. 5 Structure of the Mangrove Geodatabase for Santos region—Each image was processed identifying all patches and associated parameters

variations are more concentrated in specific areas of degradation and recovery.

Figure 8 shows the changing condition in some significant fragmentation parameters of mangrove patches from 1985 to 2014 for both study areas. The *structure and arrangement of the patches suggests that the Santos region is more susceptible to changes,* in particular a diminishing number of patches and the total perimeter and increasing of total area indicating a coalescence of mangrove patches and increasing spatial contiguity, while in Cananéia, the variation is less significant (Fig. 8a). It is important to consider that the high variation in the number of patches was not necessarily related to appearance or disappearance of mangrove patches but surpasses the treshold of the 30,000 m^2 limit of identification. Figure 8b (number of patches) and 8c (mean patch size) also shows a more variable condition in Santos compared to Cananéia, which clearly indicates that the mangrove fragments have been submitted to more dramatic variations over the time. Figure 8d (main shape index) shows how the mangrove fragmets are more regular (mean shape index is 1 when all patches are circular and increases as the patch shape becomes more irregular), despite that there were few variations in time (which is expected) the mangroves in Cananéia region presents slightly more complex forms which probably results from the presence of a higher concentration of tidal channels in the area.

The clearer example of such characteristics is the area of Cubatão in the Santos region (indicated in the square in Fig. 9) where large areas of vegetation with characteristics quite similar to mangroves has grown substantially in recent years. This example shows how a fragment can dramatically change in a relatively short period of time.



Object Change Examples	Characterized by	Geodatabase Parameters	Method
	Changes in dimensions	Area, perimeter, MSI,	Extract
	Changes in form	Fragmentation and Form Indices	Patch analyst
	Changes in complexity	Fragmentation and Form Indices	Patch analyst
	Split	ID subgrouping	Database referencing
	merge	ID grouping	Database referencing
	distance between objects and selected features	Distance to Channel Distance to AIA Distance to Inlets	Distance analyst/ "Near"
	changes in Spectral parameters	NDVI, Tassled Cap GREENESS (Mean, minimum, max, std deviation)	Zonal Statistics

Fig. 6 examples of object (patches) time changes developed in this work

Once each fragment is stored in the geodatabase as an object, it is possible to access a specific interest area (containing one or more patches) and correlate it with other parameters, and identifying which variables (spectral, spatial or topological) can be correlated with each other. In the case of the Cubatão area, particularly, it was possible to observe that the increase of area and patch areas and number of patches have not been followed by a significant change in NDVI and other vegetation index values which suggests that despite that the classification tools have indicated the presence of mangrove forests, the vegetated areas are sparse, with shorter trees with visible soil background. In fact, a field aerial survey has shown that such areas are covered by a scattered and unhealthy wetland vegetation mixed with some typical mangrove species such as *Rizophora Mangle* (Fig. 9).

On the other hand, the spectral characteristics derived from vegetation indices in Cananéia showed significantly higher values of greeness and NDVI in mangroves patches, *which also suggests* that the conditions of mangrove fragment changes are been driven by sedimentary processes in the estuary but not do not significantly change in the canopy density within the fragments, as also indicated by local analysis done by Schaeffer-Novelli et al. 2000, Cunha-Lignon et al. 2009, 2011.

The development of the geodatabase allowed for devising organization and hierarchies of information sets that can support conservation monitoring proposals since it can deal with detailed samples and estuarine scales, which also allows for interoperability and correlation between local and regional processes. In terms of conservancy and assessment of habitats and biodiversity, this work was designed to establish a framework to monitor and analyze different sets of environmental data at three levels of detail or precision that can be used to characterize and map mangroves: estuary, fragment/patch and sample in a multi temporal dataset (Fig. 10).

The geospatial database can contain several levels of spatial and spectral information about mangrove fragments, which could be an important first step for developing appropriate *assessment and prediction* methods *for coastal management since it can handle and explore enormous amounts of* georeferenced data and can offer a simple but reliable *tool for coastal monitoring*. Potential *extension of the proposed method* could include the gathering of additional data through fieldwork and direct observation and modeling the mangrove interactions with other feature classes such as urban areas and water bodies.

The mangroves can be a very good test for wider application of such methods since it shows: (a) a relatively

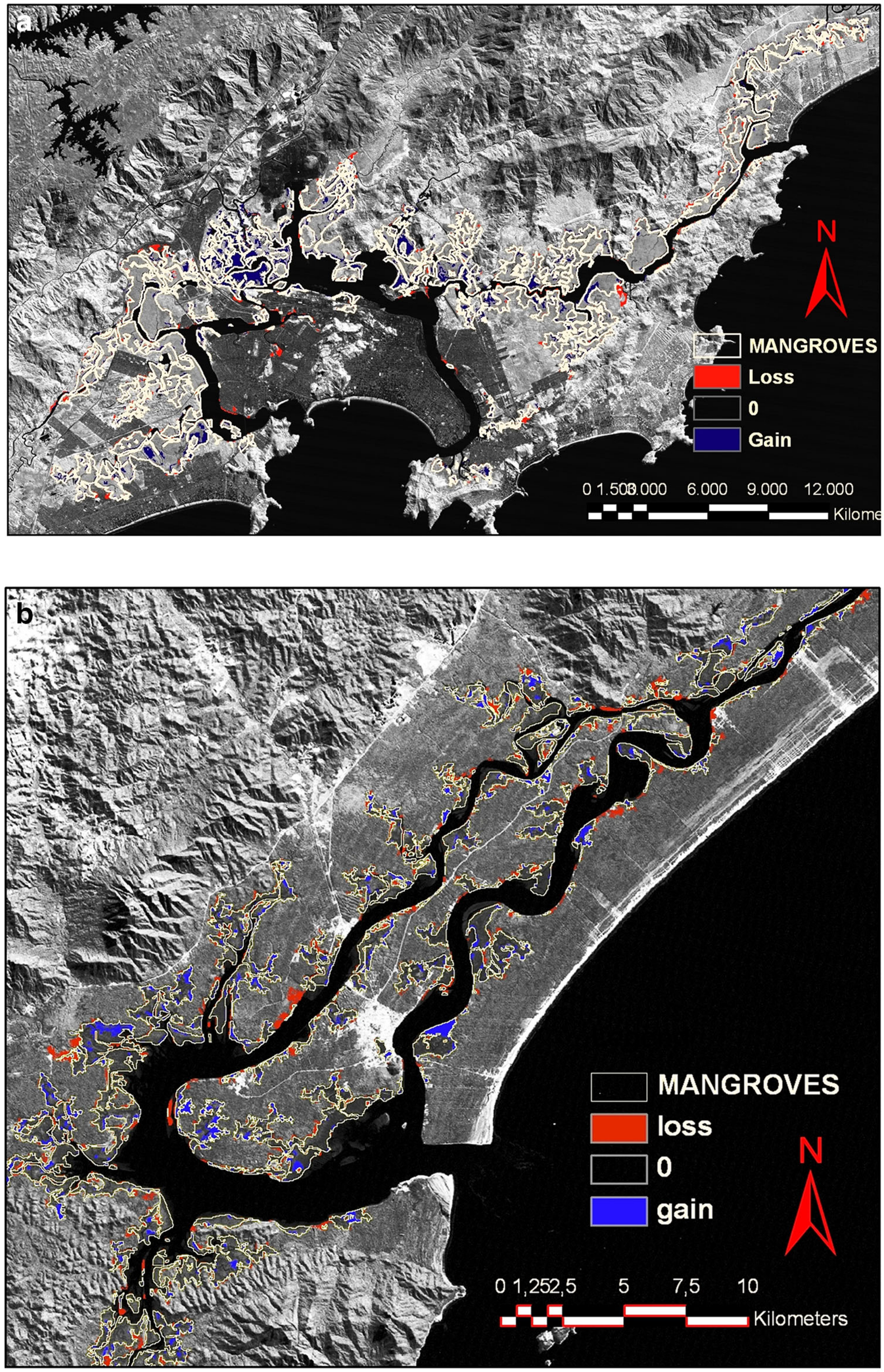


Fig. 7 Variations in mangrove formations in the Cananéia Region (**a**) and Santos Region (**b**) from 1985 and 2014. The area indicated in detail in (**b**) is the Cubatão Region (Fig. 9)

specific spectral signature which facilitates segmentation and classification. (b) a specific geographic setting, occurring always in an intertidal, flat and near channel environments which allows for determining quite accurate positioning. (c) a relatively low biodiversity what allows a controlled analysis of the historic environment parameters.

The examples of Santos and Cananeia are particulary interesting since they showed different behaviors related to responses to diverse aspects of environmental changes. While a more stable and conserved area such as Cananéia showed quite a few changes in terms of NDVI and vegetation indices (i.e. canopy density), it can be quite

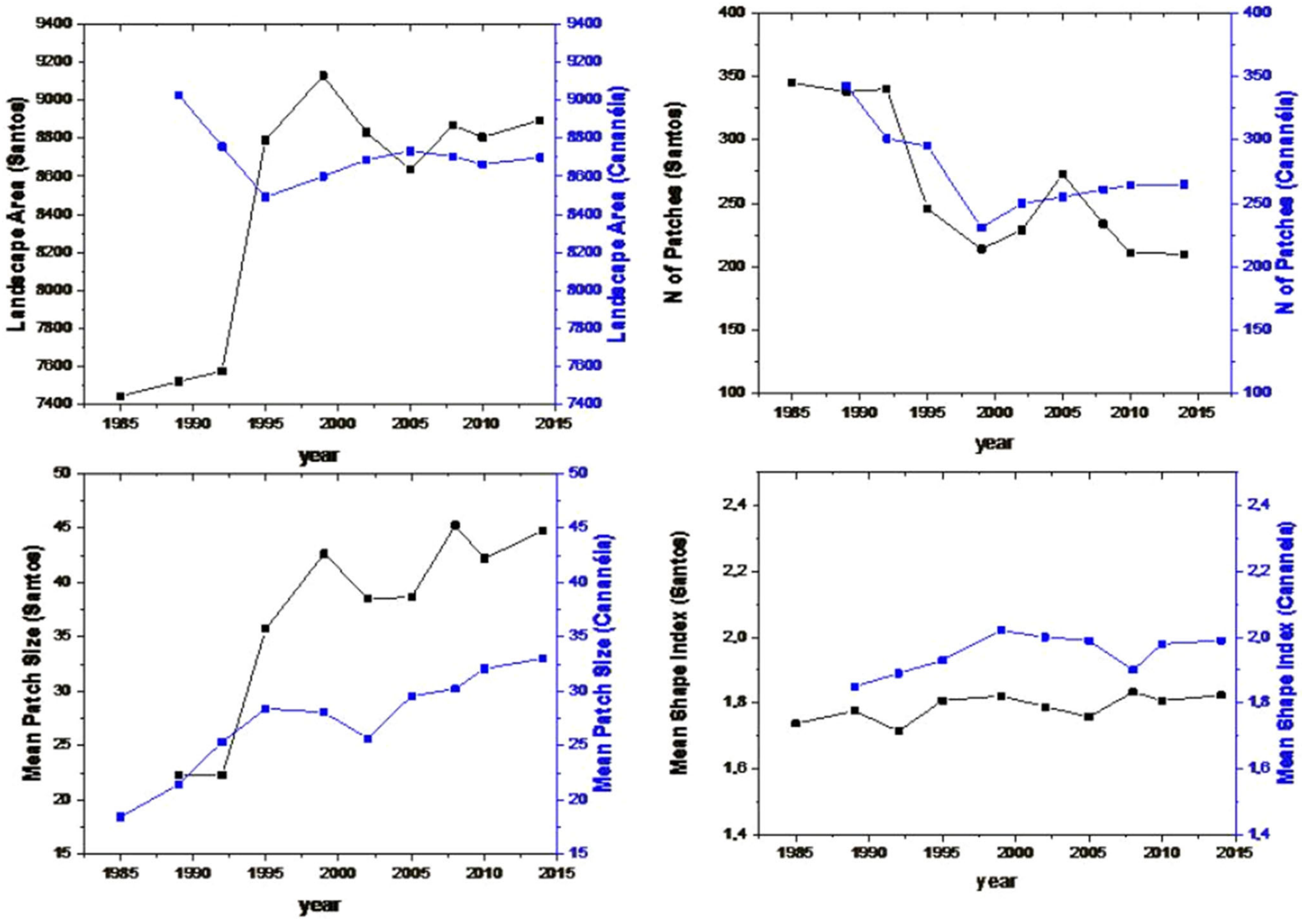


Fig. 8 Patch analysis results for Cananeia (*blue*) and Santos (*black*) estuaries. **a** Total mangrove area, **b** Number of patches, **c** Main patch size, **d** Main shape index

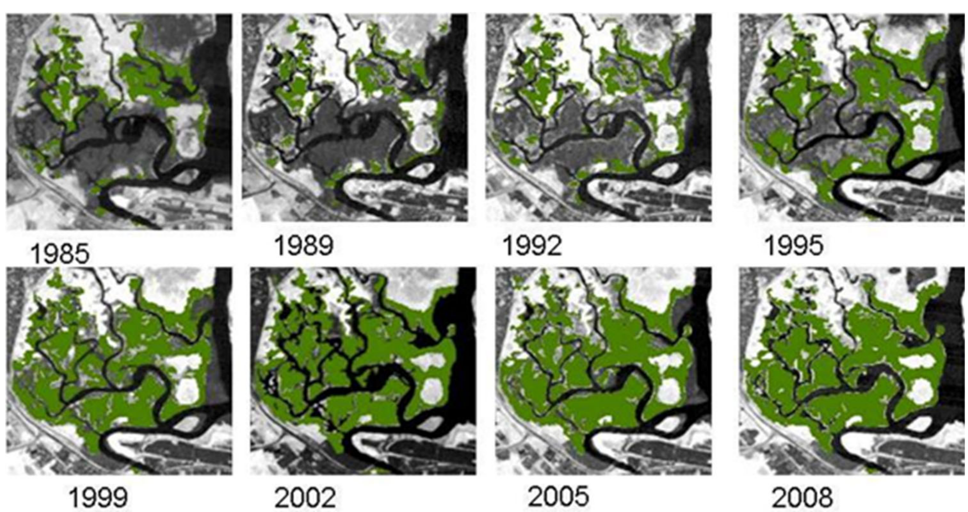


Fig. 9 Evolution of mangrove coverage of the Cubatão region (in detail from the Fig. 7b) from 1985 to 2008—The *green area* is associated with mangrove formations classified from Landsat Images

susceptible to changes due to circulation and estuarine hydrodynamics and their related factors (e.g. ersoion or sedimentation) that can be characterized by sparse changes in the patches along the main channel of the estuary (in particular near the inlet) and with no significant variation in the spectral vegetation characteristics (defined by NDVI and vegetation indices). In the Santos Region, the enviromental pressure is more related to urbanization and local

Fig. 10 Oblique aerial photoghraph showing a "recovering patch" of mangrove characterized by sparse vegetation and lower values for NDVI

anthropic pressure characterized by local and concentrated regions from nearby industrial and urban areas. The main remarkable feature identified is that the identified mangrove patches had been slowly growing in terms of area and agregating patches but the recovery of the vegetation health and vigor present a much slower recovery. All these characteristics were only obserbable due to the relaltionship between different variables (spectral, spatial and topologic) at diferent scale levels of analysis, which could be organized systematically with an hierarchical geodatabase.

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