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Remote sensing in the study of Brazilian mangroves: review, gaps in the knowledge, new perspectives and contributions for management*

Luciana Cavalcanti Maia Santos[@, a]; Marisa Dantas Bitencourt [a]

ABSTRACT

The incidence of anthropogenic pressures and the richness of mangrove areas in Brazil highlight the importance of multiscale/multitemporal studies, by the use of remote sensing technology, to provide information and data for Integrated Coastal Management. This review presents and discusses the applications and limitations of different remote sensing products for the study of Brazilian mangroves, shows the application of these tools for coastal management, and highlights gaps and new perspectives in this field of study. In the last three decades, the use of aerial photography and Landsat images, in a qualitative approach, predominated in the study of Brazilian mangroves, while images of other optical sensors and Synthetic Aperture Radar images, in a quantitative approach, are still expanding. The use of these remote sensing tools has generated very important results for the ecological knowledge of the ecosystem, for the planning and sustainable use of mangroves in the face of human pressures and for decision making in the integrated coastal management, in local, regional and national levels. Despite these advances, there are gaps and new perspectives of studies such as: use of new optical images with high spectral and spatial resolutions for mangrove species mapping; SAR images to estimate above-ground biomass; the use quantitative approaches as OBIA and vegetation index and calibration of remote sensing data with field data to estimate biomass. Here we show a framework to aid in the selection of appropriate remote sensing tools for studying mangroves in the perspective of integrated coastal management.

Keywords: satellite images, aerial photographs, SAR images, geoprocessing techniques.

RESUMO

Sensoriamento remoto no estudo de manguezais do Brasil: revisão, lacunas no conhecimento, novas perspectivas e contribuições para a gestão

A incidência de tensores antrópicos e a riqueza de áreas de manguezal no Brasil destacam a importância de estudos multiescalares, com visão sinóptica e multitemporal sobre esse ecossistema, por meio da utilização do sensoriamento remoto. A presente revisão apresenta e discute as aplicações e limitações de diferentes imagens obtidas por sensoriamento remoto no

[@] Corresponding author to whom correspondence should be addressed.

[a] Universidade de São Paulo, Instituto de Biociências, Departamento de Ecologia, Laboratório de Ecologia da Paisagem e Conservação (LEPaC), R. do Matão, 14, Butantã, São Paulo, SP, 05508-090, Brasil. E-mails: Santos <santos.lucianacm@gmail.com>; Bitencourt <tencourt@ib.usp.br>

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estudo do ambiente e da vegetação de manguezais do Brasil, destaca a aplicação dessas ferramentas para a gestão, bem como evidencia lacunas e novas perspectivas nessa área de estudo. Nas últimas três décadas, o uso de fotografias aéreas e imagens do Landsat, em uma abordagem qualitativa, predominaram no estudo dos manguezais brasileiros, enquanto imagens de outros sensores ópticos e de radar de abertura sintética, em uma abordagem quantitativa, ainda estão em expansão. O uso dessas ferramentas tem gerado resultados muito importantes para o conhecimento ecológico do ecossistema, para o planejamento e uso sustentável dos manguezais em face de pressões antrópicas e para a tomada de decisões na gestão costeira integrada, em nível local, regional e nacional. Apesar desses avanços, existem lacunas e novas perspectivas de estudo, como: uso de novas imagens ópticas com alta resolução espacial e espectral para o mapeamento de espécies vegetais de manguezal; imagens SAR para estimar a biomassa total, uso de abordagens quantitativas como classificações baseada em objeto (OBIA) e índice de vegetação, além da necessidade de calibração de dados de sensoriamento remoto com dados de campo para estimar a biomassa. Esse trabalho apresenta uma estrutura metodológica que auxilia na seleção de ferramentas de sensoriamento remoto apropriadas para o estudo de manguezais na perspectiva da gestão costeira integrada.

Palavras-chave: imagens de satélites de sistemas ópticos, fotografias aéreas, imagens SAR, geoprocessamento digital.

1. Introduction

Mangroves are coastal forests that inhabit saline tidal areas along sheltered bays, estuaries, and inlets in the tropics and subtropics throughout the world, where they fulfill several ecological, environmental and socio-economic functions (Barbier *et al.*, 2011, 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; Feagin *et al.*, 2010; Mukherjee *et al.*, 2010). Moreover, 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). Nevertheless, due to pressures from anthropogenic activities and lack of awareness or of perseverance in conservation and management strategies already implemented and/or proposed (Farnsworth & Ellison, 1997; Primavera, 2000; Kovacs, 2000; Armitage, 2002; Dahdouh-Guebas *et al.*, 2002, 2005b; Feagin *et al.*, 2010, Satyanarayana *et al.*, 2013), mangrove forests are disappearing worldwide at rates of 1 - 2% per year (Valiela *et al.*, 2001; Alongi, 2002; FAO, 2007; Duke *et al.*, 2007). This indicates that we face the prospect of a world deprived of the services offered by mangrove ecosystems, perhaps within the next 100 years (Duke *et al.*, 2007).

Brazil shows the second largest mangrove area in the world (13,000 km^2), accounting for 8.5% of the world's coverage and 50% of South America's (FAO, 2007; Spalding *et al.*, 2010). The ecosystem is distributed along the Brazilian coast, from the far north, in Oiapoque River (Amapá State) to the southernmost mangrove limit in Laguna (Santa Catarina State) (Schaeffer-Novelli *et al.*, 1990). Over 80% of Brazil's mangroves are found in a complex of deltaic systems along the north coast, where are found one of the world's largest contiguous mangrove systems (Spalding *et al.*, 2010; Nascimento *et al.*, 2013). On this region, wet conditions allow for the growth of individual trees up to 40 m in height (Spalding *et al.*, 2010). The Brazil northeast coast shows roughly 10.6% of this country's mangroves, where the ecosystems are largely restricted to estuaries and coastal lagoons, with trees reaching up to 30 m (Schaeffer-Novelli *et al.*, 1990; Magris & Barreto, 2010; Spalding *et al.* 2010). Moving southwards occurs about 6.4% of the Brazilian mangroves, where lagoons and estuaries continue to predominate, with a number of important formations behind barrier islands. The trees can reach up to 10 m (Spalding *et al.* 2010). Although, various decrees and laws in three levels of governance: federal (national), state (regional) and municipal (local) legally enforce the conservation and management of Brazilian mangroves (Santos *et al.*, 2014), these forests have been affected by a variety of anthropogenic activities, resulting in losses higher than 50.000 ha between 1980 to 2005 (FAO, 2007).

The richness of mangrove areas in Brazil and the incidence of anthropogenic pressures on this ecosystem highlight the importance of studies and monitoring researches by the use of multi-scale tools, providing information on local, regional and national levels, which are very important for the integrated coastal management. This approach provides synoptic and multi-temporal views of the processes that take place in the environment and vegetation of this ecosystem. Such studies are developed with the use of remote sensing, GIS (Geography Information Systems) and geoprocessing tools.

Remote sensing is the technology to obtain information about an object, area or phenomenon without physical contact, based on the interaction of electromagnetic radiation and the different materials of the scene (Lillesand *et al.*, 2008; Novo, 2011). Sensors are devices that capture the electromagnetic energy from objects, phenomena and surface features such as vegetation, soil, rocks, water bodies, houses, buildings and highways, and turn it into data, images, or other products interpretable by humans (Luchiari *et al.*, 2009). To obtain information about an object, area or research phenomenon, images produced by remote sensors, such as aerial photographs, images obtained by multispectral optical sensors (usually referred as satellite images) and radar imagery are interpreted using techniques of visual analysis and/or digital processing (Jesen, 2009). At this stage, the images are processed and analyzed in GIS environments or by geoprocessing software, which enables the generation of new information or maps derived from the original data (Florenzano, 2002).

Remote sensing GIS-based studies provide a synoptic view, in macro spatial and multitemporal scales, which is not possible to obtain by *in-situ*-based studies. Therefore, these tools can aid in practical issues of coastal management, such as monitoring, at distance, of the fulfillment of environmental laws in coastal areas. In the case of mangrove ecosystem, these tools are specially important for the multitemporal monitoring of these forests and anthropogenic activities, giving subsidies for management, conservation and decision-making support (Santos *et al.*, 2014). In addition, accurate mapping of these environments is essential to the scientists who focus on their ecological functioning (Giarrizzo & Krumme, 2008; Souza-Filho *et al.*, 2011), thus important tools for planning and optimizing the fieldworks, a key step for the establishment of relations between the studied phenomena and the responses observed on the images and data produced by remote sensors.

In the worldwide context, since the last 20 years remote sensing technologies have played a central role in detecting and analyzing changes in the extent and spatial pattern of mangrove forests resulting from natural and/or anthropogenic forces (Heuman, 2011). In the Brazilian context, the first studies using remote sensing images for mangrove analysis started in the 80's, with the use of aerial photographs and satellite images for mapping these forests and detecting spatio-temporal changes (e.g., Espíndola, 1986a, 1986b; Abdon *et al.*, 1986; Herz, 1988; Braga *et al*, 1989; Machado 1992). The use of GIS and remote sensing tools for studying Brazilian mangroves has intensified and spread only from 2002, with publications in refereed journals and increase in the number of dissertations and thesis. This review aims to present and discuss the applications and limitations of different remote sensing tools for the study of Brazilian mangroves, showing the application of these tools for coastal management as well as presenting gaps in knowledge and new perspectives in this field of study.

2. Materials and Methods

A bibliographical research was carried out for scientific works and studies, including the categories of scientific articles, books, dissertations, thesis and full papers published in conference proceedings, which used remote sensing tools to study Brazilian mangroves. For the research of scientific articles we used the database of *Web of Science*, *Scopus* and *Scielo*. To research for books, thesis and dissertations we used the online library catalogs of federal and state Brazilian universities and of the National Institute for Space Research (INPE). Additionally, it was used the Brazilian Digital Library of Thesis and Dissertations (http://bdtd.ibict.br/vufind/), which brings together in one search portal, thesis and dissertations developed in the country and by Brazilians abroad. To research for full papers published in conference proceedings, we considered the online library of Remote Sensing Brazilian Symposium, which contains the collection of the proceedings of these symposia since 1978 to 2015 (http://www.dsr.inpe.br/sbsr2007/biblioteca/).

The key-words used in the bibliographical research were: *mangrove*, *Brazilian mangroves*, *Brazil mangroves, remote sensing*, *satellite images*, *aerial photography*, *radar images*, *SAR images*. We considered only works and studies that used remote sensing tools for studying the environment, ecosystem or vegetation of Brazilian mangroves. In the selected works and studies we analyzed in detail the section material and methods, from which the remote sensing tools and techniques were underlined, the sections results, discussion and conclusions, from which we highlighted relevant and new results for the analysis of vegetation cover (loss due to natural and anthropogenic impacts), vegetation succession, discrimination of physiographic, mangrove vegetation types and mangrove plant species, erosion and progradation in mangroves, and the importance of these tools in the field of Brazilian mangrove and coastal management. The studies were separated and categorized based on the type of tool used and its spatial resolution. The period considered for the bibliographical research started from the oldest record in 1986 (e.g., Espíndola, 1986a, 1986b; Abdon *et al.*, 1986) up to 2015. It was revised a total of 92 works and studies applying remote sensing to study Brazilian mangroves.

3. Results and discussion

Since the late 80's different types of remote sensing images, such as aerial photographs, optical imagery and active microwave (SAR - Synthetic Aperture Radar) data, have been used for analyzing the environment and vegetation of Brazil's mangroves in several studies (Table A in SI-I). These studies apply different techniques to process the information obtained by remote sensing (Table B in SI-I). Visual analysis (qualitative approach), based on interpretation of elements such as color, texture, shape, size, structure and position, was the most commonly used technique in the study of Brazilian mangroves. According to Dadouh-Guebas *et al.* (2006) visual interpretation of aerial photographs is the most efficient and inexpensive method in the light of ecosystem monitoring research in developing countries, which are often unable to cope with the development or the cost of acquisition of commercial space-borne imaging.

Digital analysis (quantitative approach), using techniques as supervised and unsupervised classifications, segmentation, vegetation index and object-based-image-analysis (OBIA) were applied by less studies of Brazil's mangroves (Table B in SI-I), despite its importance and the recent growth since 2004. In the international context, these techniques have been wildly used with high rates of accuracy (e.g., Green *et al.*; 1998; Kuenzer *et al.*, 2011). In both cases, qualitative and quantitative approaches, it is important to note that since mangroves grow at the land-sea interface, three major features contribute to the pixel composition in remotely sensed imagery: vegetation, soil (usually muddy) and water (Kuenzer *et al.*, 2011). Thus, visual interpretation and automatic techniques must consider this in the mangrove analysis.

In Brazil, the major advance in mangrove studies by quantitative approaches was the introduction of methods based on the spectral response of the targets, supported by computational algorithms (supervised and unsupervised classifications and segmentation), which can also be complemented by visual analysis, giving more accuracy to the method employed. Moreover, quantitative techniques, such as vegetation index enabled other parameters of vegetation to be analyzed, such as green biomass, canopy closure, discrimination of plant species based on the spectral response, which is not possible with qualitative techniques, allowing a better understanding of the ecosystem ecological aspects. More recently, techniques of object-based classifications have been applied in some studies and showed a high potential to large and small scale discriminations.

Different remote sensing tools were applied in the study of Brazilian mangroves (Table A in SI-I), showing different characteristics and spatial resolutions which generate different uncertainties on the discrimination and quantification of vegetation, soil and water. Thus, studies were analyzed according to the type of tool applied, also considering their spatial resolution.

3.1 Studies of Brazilian mangroves by aerial photographs

Aerial photographs record the information of energy reflected by targets in the visible and near infrared regions and have been widely used in the mapping and evaluation of mangrove areas worldwide (Heuman, 2011). Aerial photographs at scales larger than 1:50,000, have high spatial resolution, allowing detailed mapping of mangrove cover as well as the discrimination of mangrove plant species (e.g., Krause *et al.*, 2004; Dahdouh-Guebas *et al.*, 2006). Thus, the use of this tool has been designed for obtaining information on local to regional scales, especially in cases which past data are not available and field data were not collected (Kuenzer *et al.*, 2011; Reis-Neto, *et al.* 2011). Moreover, aerial photographs are very suitable for highly detailed mapping in very small and narrow coastal environments as well as for the evaluation of mapping procedures performed with lower-resolution data (Kuenzer *et al.*, 2011).

One of the limitations of the use of aerial photographs is for mangrove mapping over large geographic areas (Heuman, 2011), due to the need to obtain a large number of aerial photos to cover the area of interest. The quality of images obtained by aerial photographs, particularly images before the 90's, and shading problems caused by clouds should also be considered. Furthermore, the application of quantitative techniques is also limited and in general visual analysis is applied, which could introduce interpretation and discrimination errors due to subjectivity of the interpreter. On the other hand, this material provides information on a broad timescale in periods prior to the availability of satellite images and is useful for detecting long-term spatio-temporal changes and monitoring of mangrove forests (Dahdouh-Guebas *et al.*, 2006; Heuman, 2011). Aerial photographs are more accessible to developing nations in which the majority of the world's mangroves grow and they can provide very rapid assessments for monitoring changes (Dahdouh-Guebas *et al.*, 2006) in times of crisis (Heuman, 2011).

In Brazil, the first three initial studies of mangrove areas by aerial photographs used photo-interpretation (visual analysis) of such material into analogical form in black and white (e.g., Herz, 1988; Braga *et al.*, 1989; Machado, 1992). The most pioneering study using this tool was the thesis of Herz (1988), developed in the Southeastern Brazil (Estuarine System of Cananéia-Iguape, São Paulo). This author used aerial photographs to discriminate different types of mangrove forests, based on visual interpretation, especially on the elements of tone and texture, classifying them into tall dense mangrove, short dense mangrove, scattered mangrove and salt marsh. In addition to these tools, Herz (1988) also used quantitative techniques to classify satellite images TM/Landsat and spectroradiometer on the field to record the spectral responses of different mangrove species.

The study of Braga *et al.* (1989) was the second published work. These authors used aerial photographs from 1974 and 1988 to discriminate and quantify changes in mangrove forests due to the introduction of human activities, such as a port and infrastructure to an industrial complex, in Northeastern Brazil (Suape, Pernambuco). Based on the photo-interpretation and temporal analysis, these authors discriminated three conservation status of mangrove forests: preserved, degraded and regenerated. They also quantified the area of loss, flooding and landfill of mangroves. In the photo-interpretation, Braga *et al.* (1989) considered many elements as: size, prevalence, form, texture, density, hue, and other factors such as topography and hydrography.

The third study published was the master thesis of Machado (1992). This author used a time series analysis of analogical aerial photographs of the years 1977, 1986 and 1987 to evaluate an oil spill impact on the vegetation cover of mangrove forests located in Southeastern Brazil (Canal de Bertioga, São Paulo). This study discriminated changes in mangrove cover, which may be associated with different stages of the vegetation responses due to the effect caused by the oil. Among the changes, were highlighted: gaps, bare soil, clearing and spaced canopy, decreased in density. The main photo-interpretation elements considered by this author were tone, texture and shape.

These three pioneer studies using remote sensing tools (aerial photography) and qualitative interpretation techniques to study Brazilian mangroves had and still have importance for the ecosystem management. For example, they serve as past database on the extent and conservation status of mangroves. They also quantified losses in mangrove area due to anthropogenic pressures, as oil and land use for port and industrial complexes, important data for the development of coastal environmental planning. These studies gave light to the importance of using these tools and multi-temporal approaches to generate fundamental data and information for coastal management.

With the increasing development of GIS and geoprocessing software for digital image analysis, analogical aerial photographs have become digitized and thus they can be analyzed in computing environments. More recently, the production of digital aerial photographs and color orthophotos allowed these images to be directly used in GIS, expanding the possibilities of analysis. The use of these tools, especially considering historical data, in the study of Brazilian mangroves has allowed the evaluation and monitoring of large-scale changes due to anthropogenic pressures, as loss and vegetation dynamics in areas under pressure from urban and industrial expansion (e.g., Bernardy, 2000; Oliveira, 2001; Melo, 2008; Menghini, 2008; Cunha-Lignon *et al.*, 2009; Santos, 2009; Santos A.L.G., 2010) and mangroves impacted by oil spill (e.g., Santos *et al.*, 2012). Others authors have been using aerial photographs to map mangrove forests and to discriminate anthropogenic pressures on these areas (e.g., Lardosa, 2011) and to assess mangrove vulnerability to urban occupation (e.g., Coelho, 2008).

Aerial photographs have also been used to assess the vegetation dynamics of Brazilian mangroves from natural processes such as: erosion, progradation, natural recovery (e.g., Vale, 1999, 2004; Cunha-Lignon, 2005; Reis-Neto *et al.*, 2011, 2013), gap dynamics (e.g., Espinoza, 2008; Espinoza, *et al.*, 2009); discrimination of mangrove plants species (e.g., Krause *et al.*, 2004) and shifts between salt marshes and mangrove (e.g., Portugal, 2002; Lugli, 2004). From these works we highlighted the study of Portugal (2002), which used a spatio-temporal analysis of aerial photographs, combined with data from mangrove forest structure, microtopography survey and sedimentary dynamics, to developed scenarios of mangrove dynamics in response to sea level elevation. This study revealed a dynamic behavior of mangroves, involving propagation of pulses (toward the bay) and colonization of pulses toward a hypersaline plain (salt flats).

Thus, these studies demonstrate the importance of aerial photographs to study the dynamics of vegetation and to monitor natural changes in mangrove extent and cover, contributing to the ecological knowledge of the ecosystem as well as the identification and monitoring of human impacts, both information important for the ecosystem and coastal management.

3.2. Studies of Brazilian mangroves by medium-resolution optical imagery

Medium-resolution optical imagery (spatial resolution between 5 and 80 meters) provides a multitemporal and synoptic view of extensive areas, making available information in different bands of the electromagnetic spectrum (Florenzano, 2002). Currently there is a significant number of medium-resolution optical sensor systems that can be used to accurately map coastal wetlands (Rodrigues & Souza-Filho *et al.*, 2011) such as: MSS (Multispectral Scanner), TM (Thematic Mapper) and ETM (Enhanced Thematic Mapper) from the Landsat satellites; CCD (High Resolution Imaging Camera) and IRMSS (Infrared Multispectral Scanner) from CBERS satellites (China-Brazil Earth Resources Satellite Program); ASTER satellite (Advanced Spaceborne Thermal Emission and Reflection Radiometer); HRV (Haute Resolution Visible) from SPOT satellite (*Système Probatoire d'Observation de la Terre*); LISS (Linear Imaging Self-Scanning Sensor) from IRS satellite (Indian Remote Sensing Satellite) and AVNIR (Advanced Visible and Near Infrared Radiometer) from ALOS satellite (Advanced Land Observing Satellite). From this diversity, images from Landsat, CBERS and IRS are freely available from the INPE's website.

Medium-resolution techniques are excellent for the mapping of ecosystems (however, usually not at the species level), the monitoring of large-scale changes, the analyses of regional environmental relationships, and the assessment of the condition of mangroves (vigor, age, density, etc.). Global mangrove loss numbers have been derived solely from the analysis of medium-resolution data (Kuenzer *et al.*, 2011).

From the diversity of medium-resolution images, the freely availability of Landsat images has increased the use of satellite images in different areas of knowledge, especially for management purposes. In the remote sensing of Brazilian mangroves, the first studies using satellite images were developed in the INPE using Landsat MSS and TM images. The studies of Abdon *et al.* (1986, 1988) were the pioneers to use these images in a multitemporal analysis to map and detect deforestation in mangrove areas, as well as, to classify mangrove forest structure in tall and short stands.

After these, most studies have used images of Landsat TM and ETM + (Table A in SI-I), due to the freely available and longevity of its sensors. Fewer studies employ images of other optical medium resolution sensors (Table A in SI-I). In overall, medium-resolution optical imagery has been applied to discriminate, measure and quantify the extent and changes of Brazilian mangroves at regional (e.g., Souza-Filho, 2005; Maia & Lacerda, 2006) and local scales (e.g., Pires, 1992; Noernberg *et al.,* 2006; Vieira, 2007; Medeiros 2009; Silva, 2009; Santos *et al.*, 2014). Nevertheless, a recent study (e.g., Magris & Barreto, 2010) was developed at the national scale and mapped mangroves as well as assessed the protection of this environment across coastal protected areas in the entire Brazilian coast. These authors used Landsat TM images and visual interpretation. They found that most of the Brazilian mangroves (83%) are located within protected areas, mainly of sustainable use, but they are concentrated on the North and Southeast coast. According to them, new protected areas should be established in other eco-regions, such as in the northeastern, in order to ensure sustainable management of mangrove resources. This is an important study because it is the most recent mapping of Brazil's mangroves at the national scale, and addressed important issues for the management and conservation of this ecosystem.

The availability of medium spatial resolution satellite images for about three decades has enabled temporal studies of mangrove vegetation cover (Kuenzer *et al.*, 2011). These images are useful to assess the extent and intensity of changes, but they are not suitable for analysis on detailed scales, due to the coarse spatial resolution (Krause *et al.*, 2004).

Time series of medium spatial resolution images have allowed the identification and quantification of anthropogenic changes in the coverage of Brazilian mangroves, such as: losses of mangroves due to landfills and human occupation (e.g., Bonetti-Filho, 1996; Martins, 2008; Martins & Wanderley, 2009; Araújo, 2010), aquaculture activities, tourism, urban expansion, agriculture (e.g., Guimarães, 2007; Guimarães *et al.*, 2009; Medeiros, 2009; Santos *et al.*, 2009; Jesus, 2010; Silva, 2012; Santos *et al.*, 2014; Godoy, 2015), road construction (e.g., Krause *et al.*, 2004) and detection of cryptic ecological degradation, a process in which occurred increase of macrophytes flats in mangrove areas, masking the degradation of the site due to hydrological changes (e.g., Cunha-Lignon & Kampel, 2011).

Natural changes have also been detected by these tools, such as loss of mangroves by erosion processes (Krause *et al.*, 2004; Araújo, 2010; Jesus, 2010; Silva, 2010), increase in mangrove area by progradation processes as dense settlement and development of this vegetation on tide muddy plains and barrier islands (e.g., Alves *et al.*, 2003, Cunha-Lignon *et al.*, 2011; Silva, 2012) and expansion into new sedimentation areas and in old saltwork area (e.g., Reis-Neto *et al.* 2013; Godoy, 2015), detection of vegetation regeneration (e.g., Araújo, 2010), as well as mangrove dynamics, including increase and decrease of area and the intrinsic relationship between mangroves and salt flats (e.g., Almeida, 2010; Almeida, *et al.*, 2011). Kampel *et al.* (2005) used a multi-temporal analysis of TM/Landsat-5, ETM+/Landsat-7 and CCD/CBERS to detect mangrove area changes and dynamics, and their results confirmed the use of CCD/CBERS imagery as an appropriate source of information to monitor this important ecosystem at reduced costs, as also highlighted by Santos *et al.* (2014) and Santos & Bitencourt (2013).

Silva *et al.* (2013) used multi-temporal analysis of TM/Landsat-5 to map changes in mangrove forests, detecting that mangrove forest in protected areas showed an expansion in extent. By these results, the authors highlighted the importance of protected areas in mangrove forests, mainly in urban and metropolitan areas. Also in this perspective, the study of Lardosa *et al.* (2013) surveyed and updated cartographic data, including satellite images of TM/Landsat-5 and SPOT to produce an essential tool for the management of mangrove ecosystem, in the State of Rio de Janeiro, which is a base to implement a Mangrove Conservation Policy.

The findings showed here by the use of medium resolution satellite images are important information for the regional and local management of the ecosystem, subsidizing the development of adequate management strategies, according to the natural or anthropogenic changes affecting the mangroves. For example, in the Brazil Northeast shrimp farming is one of the main threats to mangrove conservation. Thus, remote sensing based studies allow identifying these threats and assist to delineate conservation issues to mangrove forests, as shown by the studies of Santos *et al.* (2014), Guimarães *et al.* (2009) and Medeiros (2009), in the Brazilian Northeast mangroves. In the use of medium-resolution optical imagery for mangrove studies, Brazil is following the global tendency, as found by Kuenzer *et al.* (2011), that many papers underscore the importance of medium-resolution imagery for mangrove-habitat mapping, wherein Landsat TM data have been used extensively.

3.3. Studies of Brazilian mangroves by high-resolution optical imagery

Images of optical systems of high spatial resolution (≤ 5 m) are recent products of remote sensing and sources of large-scale and detailed information about mangrove vegetation. These tools allow the discrimination and mapping of mangrove plant species or assembly of plant species, detailed characterization of the canopy structure, estimation of green biomass and leaf area index at high spatial detail (Heuman, 2011; Kuenzer *et al.*, 2011). Many of the high-detail applications that were once exclusively dependent on aerial photographs surveys can be currently developed with data obtained from high spatial resolution sensors (Novo, 2011). However, the use of these images is limited to applications that require synoptic view of large areas, because it is necessary to obtain a large number of images, which may not be available, as well as for multitemporal studies, because they are recent images which are not obtained at fixed intervals of time (Novo, 2011).

High resolution images include, for example, images of the panchromatic band from sensors as HRG (High Resolution Geometric) from SPOT-5 satellite, PRISM (Panchromatic Remote-sensing Instrument for Stereo Mapping) from ALOS satellite and HRC sensor (High Resolution Camera) from CBERS-2B satellite. Besides these, there are multi-spectral images of new very high resolution sensors such as GeoEye, RapidEye, QuickBird, Worldview-2, Worldview-3 and Ikonos. In the case of panchromatic images, its fusion with lower resolution multispectral images (pansharpening) is a suitable technique, allowing the generation of a final product in three colors bands and with the maximum resolution of the panchromatic image (e.g Santos, L.C.M., 2010; Bitencourt & Santos, 2013; Santos *et al.* 2014).

Studies that applied high-resolution images for analyzing Brazilian mangroves are still scarce (Table A in SI-I) and few use the potential offered by these images for quantitative and more detailed analysis, as for the discrimination of plant species. Images of the sensor Ikonos have been used for general mapping of mangroves and their vulnerability to oil spills (e.g., Andrade *et al.*, 2010), as well as discrimination of mangroves in regeneration, removed and preserved phases (e.g., Vasconcelos, 2009, Vasconcelos *et al.*, 2011). In the study of Andrade *et al.* (2010), it was highlighted the use of these images for mapping mangrove vulnerability to oil spills, which is essential as one of the first step in the development of an integrated coastal zone management. Vasconcelos (2009) and Vasconcelos *et al.* (2011) showed the application of Ikonos images for constant environmental monitoring, as to report the ecosystem dynamics in urban areas.

QuickBird imagery have been used to study the spatial-temporal dynamics of mangrove forests, including dynamic of gaps and identification of dominant plant species (e.g., Espinoza, 2008; Espinoza *et al.*, 2009), as well as serving as auxiliary data for mangrove mapping carried out with lower spatial resolution images (*e.g.*, Araújo, 2010). Santos, L.C.M. (2010) and Santos *et al.* (2014) fused the panchromatic image HRG/ SPOT-5 with the multispectral image of the CCD/CBERS-2B, creating a final product that provided information on a large scale, essential to map and characterize the mangroves and identify human pressures as shrimp farming. In this view, Tenório *et al.* (2015) evaluated the role of marine aquaculture in the conversion of mangrove forests into shrimp farms using HRG2/SPOT-5 and GeoEye satellite images obtained from the Google Earth PRO. Due to the high spatial resolution of these images the visual interpretation was an efficient tool for their study. Based on their results, they pointed out recommendations for the sustainable use of mangroves on the Amazon coast.

The production of high-resolution images has allowed the use of new image analysis techniques based on objects, called OBIA, Object-Based-Image-Analysis (Blaschke, 2010). Object-based methods use spatial neighborhood properties for classification while pixel-based approaches use solely the spectral information. OBIA emulates the expert knowledge applying classification rules in segments of the images. This classification considers space and geometric attributes and hierarchical relationships among neighborhood (Definiens, 2007). With the availability of high-resolution images and OBIA methods, remote sensing techniques can be very beneficial to monitor mangrove areas (Meneghetti, 2013). In the global context, remote sensing studies in mangrove areas have demonstrated the superiority of such procedure in comparison with the commonly used pixel-based supervised classification approach (Kuenzer, 2011). In Brazil, there are few studies that apply this technique (e.g., Vasconcelos *et al.*, 2011; Meneghetti, 2013; Silva *et al.*, 2013; Nascimento *et al.*, 2013; Almeida, *et al.*, 2014; Meneghetti & Kux, 2014; Arasato *et al.*, 2015a).

OBIA is a new remote sensing technique in the study of mangroves and it has been showing a great accuracy and applicability for more detailed mapping. For example, Almeida, *et al.* (2014) used IKONOS images and OBIA, combined with structural vegetation data (measured in the field) to map different physiographic types of mangrove forests. They mapped 4 types of mangroves: fringe, basin, transition and colonization forests. Meneghetti (2013) and Meneghetti & Kux (2014) used WorldView-2 images and OBIA (data mining technique) to land cover mapping, including mangrove areas. This study found that the new spectral bands of WorldView-2 sensor (Red Edge, Near Infrared-2 and Coastal Blue) assisted in discrimination of typical targets of coastal areas such as dunes, mangroves and tidal channels, improving the classification of land cover. Among these bands, the Red Edge allowed the discrimination and separation of the mangroves from the other classes. The results and techniques developed by these authors show the application of new underexplored tools, as the Red Edge band for mangrove mapping. The maps resulted from this study will facility the decision making for the local coastal management.

Arasato *et al.* (2015a) used WorldView-2 images, OBIA and vegetation index, to generate thematic maps of land use and cover, types of mangrove (mangrove, mangrove swamp with associated species, gaps) and mangrove species. Moreover, integrating the map of types of mangrove with LIDAR data, the authors mapped the height of the mangrove forests. This study shows a good example of integrating different techniques to high detail and biomass mangrove mapping. However, many manual edits based on visual interpretation keys were required for finishing the maps. In this case, the high spatial and spectral resolution of the images facilitated the identification and visual discrimination.

3.4. Studies of Brazilian mangroves by SAR (Synthetic Aperture Radar) images

Sensors of Synthetic Aperture Radar (SAR) operate in the region for microwave, based on the transmission of long wavelengths and detecting the amount of backscattered energy (Jensen, 2009). These sensors provide images that cover a wide geographic region, providing synoptic view of vast areas for mappings at large scales of 1: 100,000 to 1: 400,000 (Jensen, 2009). Thus, SAR images are appropriate tools for mapping mangroves in large geographic regions, such as in regional to national scales. The spatial resolution SAR images is variable according to the type of sensor and can vary from low to high, in the latter case, in new SAR sensors.

SAR images also enable the extraction of information about surface roughness, dielectric properties, moisture (Jensen, 2009) and salinity of landscape targets. SAR sensors are active systems (they have own source of energy) which allow acquiring images during the day and night. Moreover, since they operate in microwave, it is possible to generate images that are not affected by cloud cover, fog and precipitation (Novo, 2011). For the study of mangroves, these features are very important, because the ecosystem is distributed in coastal areas in tropical and subtropical regions, where the cloud cover is usually intense. In the global context SAR images have been successfully used for the study of mangroves (Heuman, 2011), providing information on the extent of vegetation, structural parameters, flood limits, health, deforestation and amount of total biomass. However, these images are limited to discrimination on the level of plant species (Kuenzer *et al.*, 2011) and to identify the border between mangroves and adjacent tropical forest (Nascimento *et al.*, 2013).

Among remote sensing techniques, synthetic aperture radar is a particularly advantageous method to monitor mangroves: images are not dependent on cloud cover and can provide information from forest understory (Pereira *et al.*, 2012). These tools provide an additional and powerful source of data for the mapping of coastal land cover under conditions that are restrictive to the acquisition of optical satellite images, such as constant cloud cover and smoke from fires (Souza-Filho *et al.*, 2011).

In Brazil, Herz (1991) conducted the first study at the national level using SAR imagery to map mangroves along the Brazilian coast. Although the importance of this study as the first to document Brazilian mangroves at national scale, it should be considered with caution as database for other mappings, because this study presents failure in the discrimination of mangroves and lacks of more integration with field studies. Other studies using exclusively SAR images (Table A in SI-I) were developed in local and regional levels, mostly on the Brazil north coast. In these studies, SAR images are mainly used to map types of mangrove forests, stages of vegetation, and loss of mangrove area due to severe erosion, despite the potential of these tools to study mangrove biomass. Souza-Filho & Paradella (2003), using visual interpretation, indicated that the mapping of mangrove forests using SAR images was facilitated due to a high contrast of mangroves with water. In another approach, Souza-Filho *et al.* (2011) indicated the applicability of multipolarized SAR images, obtained from R99B sensor from the Amazon Surveillance System (SIVAM), to discrimination mangroves. This study provided important new insights into the interpretation of coastal wetlands, such as the use of multi-polarized L-band SAR to identify and discriminate distinct geomorphic targets in tropical wetlands, as mangroves. Multipolarized airborne system may be especially useful for mapping the wetlands along the Amazon coast (Souza-Filho *et al.*, 2011). Pereira (2011) and Pereira *et al.* (2012) also used multipolarized SAR images, from the sensor PALSAR (Phased Array L-band Synthetic

Aperture Radar), for mapping and to discriminate physiographic types of mangrove forests. Pereira (2011) correlated structural parameters of the mangrove forests with backscatter signals from SAR images, for mapping mangrove structure. This study highlighted that SAR data are potential tools for mapping and study the structure of mangrove forests and the L-Band SAR data was the most effective for mapping mangrove areas, and therefore it is recommended as a tool for coastal management (Pereira *et al.*, 2012).

3.5. Studies of Brazilian mangroves by the integration of SAR and optical imagery

The combination of SAR and optical sensors images generate additional results for the production of coastal environments maps, allowing an adequate visual discrimination of the extent of mangroves (Souza-Filho & Paradella, 2005; Rodrigues & Souza-Filho 2011, Nascimento *et al.*, 2013). In the global context, the integration of these images has been important to discriminate different densities of mangrove vegetation, different age groups and types of forests based on the dominant species (Kuenzer *et al.*, 2011). In Brazil, the first studies of this type was developed by Espíndola (1986a, 1986b) who used MSS/Landsat and SAR images to discriminate 13 unites of mangroves in Cananéia-Iguape (São Paulo State). More recently, the combination of SAR and optical sensors have been used for general mangrove mapping (e.g., Santos *et al.*, 2009; Souza-Filho, 2000; Souza-Filho *et al.*, 2005; Teixeira & Souza-Filho, 2009; Rodrigues & Souza-Filho, 2011) as well as to assess and map mangrove vulnerability to oil spills (e.g., Souza-Filho *et al.*, 2009). This integrated approach also allows the discrimination of mangrove forest types and stages of vegetation (e.g., Souza-Filho & Paradella, 2002; 2005), analysis of spatio-temporal changes in vegetation cover (e.g., Lara *et al.*, 2002, Cohen & Lara, 2003; Souza-Filho *et al.*, 2006; Batista *et al.*, 2009; Costa, 2010; Dantas *et al.*, 2011;. Nascimento *et al.*, 2013) and recovery analysis of vegetation in areas degraded by human impacts (e.g., Lara *et al.,* 2002; Cohen & Lara, 2003).

In this integrated approach images of Landsat optical sensors are also the most used and those of SAR imagery are from RADARSAT-1 (C-band). Some of these studies gains relevance because they merged images of optical sensors with SAR images (e.g., Souza-Filho & Paradella, 2002; Souza-Filho *et al.*, 2005, 2009; Rodrigues & Souza-Filho, 2011), generating an integrated product which gives more detailed and precise information and results for mapping and analyzing mangroves. It is interesting to highlight the study Nascimento *et al.* (2013), which used JERS-1 SAR, ALOS-PALSAR and Landsat TM in a OBIA to map mangroves in the north region, and confirmed that Brazil is the country with the largest contiguous belt of mangrove forests, located from east of the Amazon River mouth, Pará State, to the Bay of São José in Maranhão. Nevertheless, these mangroves are experiencing significant change because of the dynamic coastal environment and the influence of sedimentation from the Amazon River along the shoreline, requiring continued observations using combinations of SAR and optical data (Nascimento *et al.*, 2013).

Considering the study of mangrove vegetation, optical images recorded the spectral information of the upper layers of vegetation such as leaves and canopy, while in certain bands (L and P) of SAR images the microwave length is capable of penetrate in the lower layers of vegetation, providing information on the structure of branches and stems. This integration of different images provides additional information, especially to evaluate the total biomass of mangrove forests (Aschbacher *et al.*, 1995; Kuenzer *et al.*, 2011). Therefore, synergistic information on structure and composition derived from radar backscatter signals and the reflectance information from the optical imagery are most promising for vegetation-mapping applications (Giri & Delsol, 1993; Aschbacher, 1995; Kuenzer *et al.*, 2011).

However, as in any remote sensing study, for this approach be effective, the integration of remote sensing results with field data is essential. This can be achieved by the development of allometric models to estimate mangrove vegetation biomass, considering the diameter and height data from mangrove trees obtained in field, and parameters estimated by remote sensing data. Nevertheless, these models are site-specific and species-specific, which limits the reliability of some estimates of biomass by remote sensing to be applied in different mangrove areas. Worldwide, studies applying this approach make use of allometric models already published in the literature (e.g., Simard *et al*., 2006; 2008). In Brazil, some allometric models were developed for mangroves on the southeast coast (Soares & Schaeffer-Novelli, 2005; Arasato *et al.*, 2015b) and northeast (e.g., Silva, 1993; Santos, 2012). More recently, the study Arasato *et al.* (2015b) integrated LiDAR, World-View-1 and field data to map and monitor mangrove structure and biomass, concluding that LiDAR data can be operationally applied in mangrove biomass estimation. Despite the potential to develop this approach for Brazilian mangroves, allometric biomass models are not available for mangroves located on the northern region, requiring field works for their generation.

3.6. Gaps in the knowledge and news perspectives

The use of remote sensing to study Brazilian mangroves are still in development and there are many new techniques and sensor images to be explored in this field of knowledge. In overall, images from medium-resolution optical imagery are the most explored, especially from

Landsat sensors (Table A in SI-I). Nevertheless, most of the studies use a qualitative approach, applying the technique of visual interpretation. The use of quantitative techniques is urgent and necessary in order to provide more reliable results, to allow comparative analysis between different areas and to provide more ecological data which is necessary to apply in management decision making. For example, vegetation index are still underexplored in the study of Brazilian mangroves (Table B in SI-I). This methodology allows to estimate green biomass of mangroves and to identify more productive mangroves, which are important information do delineate mangrove areas for conservation and fishery. Theses approaches are new perspectives which should be explored. For example, Santos (2015) and Santos *et al.* (2015, *in press*) used maps of mangrove vegetation index as input layer in a multicriteria anlaysis to map more suitable mangrove areas for fishery and conservation of the mangrove crab *Ucides cordatus*. There are many types of vegetation index indices such as Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), Simple Ratio (SR), which allow quantifying the vegetation density per area, mangrove canopy closure, gaps, green biomass, leaf area index and comparisons among different mangrove forests (e.g., Kovacs, 2004, 2005; Giri *et al.*, 2007, Santos & Bittencourt, 2013). In Brazil, this approach is underexplored and still lacks calibration from parameters collected in field. These are gaps of knowledge which should be filled by new studies.

Similarly, Brazilian mangroves lacks of studies using the quantitative analysis as OBIA, which is a classification technique that uses objects rather than just individual pixels for image analysis (Heuman, 2011). OBIA applied in high resolution images is a new and potential tool to mapping mangroves up to species level and is a new perspective to be explored in Brazilian mangrove remote sensing. Information and maps of mangrove species is crucial in management strategies. Worldwide, few studies have used OBIA to map the areal extent and change of mangroves as this approach is more commonly applied to species mapping (e.g., Krause *et al.*, 2004; Wang *et al.*, 2004a, 2004b), but this classification has potential for mapping mangrove species and extent, showing very high accuracy for classifying mangroves (Conchedda *et al.*, 2008; Heuman, 2011).

Studies using CBERS images for the analysis of mangroves in Brazil are still scarce (Table A in SI-I), despite the potential offered by these images. The CCD images have shown potential to map Brazilian mangroves in medium scale, especially to identify human pressures on mangroves located on the northeast coast. More recently, since January 2015 images from the new launched satellite CBERS-4 are available. This satellite has two sensors MUXCAM and PANMUX, the first producing images with 20 m of spatial resolution and the second images with 5 m (panchromatic) and 10 m of spatial resolution (multispectral), thus having application in many scales of study (INPE, 2015). All images from CBERS are freely available thus an important tool for monitoring mangroves. As new perspectives, CCD and the new images from PANMUX and MUXCAM can be used for monitoring mangroves and for the calculation of vegetation index. For local and high scale studies, the HRC and PANMUX panchromatic images with high spatial resolution (2.7 m and 5 m, respectively) can be merged with multispectral PANMUX images for better visual interpretation through color compositions and application of quantitative techniques, as supervised classification and OBIA (e.g., Santos & Bitencort, 2013; Santos *et al.*, 2014). Data fusion techniques can improve classification accuracy by drawing upon different data sources to maximize the dimensionality of available information (Heuman, 2011). For regional studies, the joint use of the images of these sensors images (CCD, HRC, PANMUX, MUXCAM) is an excellent method because it offers complementary information at different scales. Although the CBERS satellites are no longer in operation (CBERS-2 since 2009, CBERS-2B since 2010 and CBERS-4 since 2015) these images are a major source for short term multitemporal studies and detection of changes.

Another new perspective to be explored is the Landsat-8 satellite which images are recent and current freely available, produced since 2013. The Landsat-8 has a new sensor called OLI (Operational Land Imager) which is an optical sensor with nine multispectral bands, spatial resolution of 30 meters and a panchromatic band with a spatial resolution of 15 meters, generating images with 12-bit of radiometric resolution (USGS, 2015). The high spectral and radiometric resolution of this sensor increases the discriminatory power of digital quantitative analysis, as OBIA and supervised/unsupervised classifications, separating different types of mangrove forests. Another potential is the calculation of vegetation index and the fusion of the panchromatic band with multispectral bands, generating color compositions with a spatial resolution of 15m, which allows better visual discrimination of mangroves. Finally, the new ultra-blue band (0.43μm - 0.45μm) is indicated for coastal studies (USGS, 2015), and in the case mangrove would be useful to differentiate the vegetation fraction among the water fraction.

In the study of Brazilian mangroves, the exploration of spectral resolution did not show great progress in these three decades, and it is mostly used three to five sensor bands, although there are in the market hyperspectral sensors that produce numerous bands (e.g., CASI, AISA +, EO-1 Hyperion, AVIRIS, Hymap, Dedalus).

In the global context these sensors have been explored in the study of mangroves (e.g., Green *et al.*, 1998, Hirano *et al.*, 2003; Yang *et al.*, 2009; Heuman, 2011). Hyperspectral data provide new opportunities for mapping mangrove forests by providing a large number of very narrow bands (<10 nm) in the 0.38–2.5μm range (Kuenze *et al.*, 2011). This greatly increases the level of detail, because a characterization of the complete spectra of mangrove cover types is possible (Green *et al.*, 1998). These tools have not been explored in the study of Brazilian mangroves and are new perspectives to be considered.

Finally, the potential of SAR images to extract information about biomass of trunks, branches and aerial roots, salinity in the leaves, in soil and water as well as moisture from the vegetation of Brazil's mangroves, have not yet been explored and thus they are new perspectives that urge to be applied in this field of study. Worldwide these tools have been successfully applied to estimate above-ground biomass and structural parameters of mangrove vegetation, mainly using polarized images (Kuenzer *et al.*, 2011). The quantification of above-ground biomass is very important in the context of global climate changes, in order to identify mangroves that act as carbon stocks, which are important areas for conservation. Given their high biomass and productivity, there is increasing interest in the role that mangroves may play in global carbon budgets (Spalding *et al.*, 2010). In this context, JAXA (Japan Aerospace Exploration Agency) launched the ALOS-2 PALSAR which SAR images promise the possibility of estimating total above-ground biomass, due to the properties of the L band, the pixel of 10 m and 12-bit radiometric resolution. Nevertheless, this approach needs field validation in order to develop allometric models for mangrove biomass, which is site and species specific, thus requiring, for some sites and regions of Brazil, specially the North, the development of these models. This is a gap in the knowledge of Brazilian mangrove remote sensing that must to be filled in new studies.

3.7. Contributions for Integrated Coastal Management

The detection and extraction of data about the spatial distribution and extent of coastal ecosystems, such as mangroves, and anthropogenic activities that affect the ecosystem are essential information for the elaboration of coastal management plans (Santos *et al.*, 2014). Other important data are from the ecosystem conservation status, vegetation stages and species composition, productive, biomass, dynamics and risk of erosion and sea level rise. The use of remote sensing techniques and tools can provided this type of information in multiple scales of space and time. This data and information can be used in geoprocessing techniques, e.g., multicriteria evaluation analysis (MCE), to define more suitable areas for multiple uses in the decision making process of the integrated coastal management. For example, which mangrove areas are more suitable for conservation, or which mangrove area can be used for other human uses as fishery, shrimp farming, aquaculture or tourism? This can be answered by an integrated analysis of the data resulted from remote sensing studies, in geoprocessing analysis, like MCE (e.g., Santos, 2015; Santos et al. *in press*).

Resource allocation for use or conservation, a central issue in integrated coastal management, and requires the developing of analytical and operational evaluation tools for decision-making (Andalecio, 2010) which can be achieved by the analysis with GIS and remote sensing techniques (Eastman, 2012). In these cases which involve multidisciplinary knowledge bases, a geoprocessing procedure called Multi-Criteria Evaluation (MCE) is the more appropriate (Huang *et al.*, 2011) to achieve conservation and management use purposes. MCE provides a systematic methodology to combine the inputs with cost/benefit information and stakeholder views to rank project alternatives (Huang *et al.*, 2011).

In Brazil, since 1986, when the first studies using remote sensing tools were developed, they have been contributed with important information for mangrove and coastal management. For example, pioneers studies as Abdon (1986, 1988); Braga *et al.*, (1989) and Machado (1992) discriminated changes in mangrove due to anthropogenic impacts. Along the years, the evolution of remote sensing studies of Brazilian mangroves clearly demonstrates a large contribution in the context of coastal management and mangrove ecosystems, providing data and information about the ecosystem status and extent in past periods and data about natural and anthropogenic changes, which are important for designing management and land use plans in coastal zones. In addition, some studies detected the importance of the establishment of protected areas in mangroves, (e.g., Silva *et al.*, 2013) and as one of the main important, Magris & Barreto (2010) identified the need in the national scale for the implementation of protected areas mainly in the northeast of Brazil.

Here we showed various applications of remote sensing tools to study Brazilian mangroves and their applicability to aid in the ecosystem and coastal management. The usefulness of such tools depends on the quality of the data, on the expertise of the technical team and on the availability of information on the geometric accuracy. All of these aspects must be addressed and quantified in order to provide a sound scientific basis for integrated management policy formulations (Hunsaker *et al.*, 2001; Krause *et al.*, 2004). Additionally, all tools have potentialities and limitations, thus a main step is to choose the adequate tool and technique among the diverse available. The selection of the appropriate images and techniques will primarily depend on the scale and objectives of the study as well as on the financial viability to acquire commercial satellite images. We summarized the applications and limitations of different types of remote sensing images for the study of mangroves in Brazil (Table C in SI-I), which can serve as a framework guide for those interested in applying these tools to study mangroves and to produce data and information to aid in coastal management.

4. Conclusions

In the last three decades, the use of aerial photography and TM and ETM + images, from Landsat series, in a qualitative approach, predominated in the study of Brazilian mangroves, while images of other optical sensors (e.g., CCD/CBERS, HRV/SPOT, IKONOS) and SAR images, are still expanding and gaining expression in this field of study. The use of these remote sensing tools has generated very important results for the ecological knowledge of the ecosystem and to support the planning and sustainable use of mangroves in the face of human pressures and for decision making in the integrated coastal management, in local, regional and national levels. However, there are still gaps in this research area. One is the lack of calibration of remote sensing data with field parameters for the estimation of vegetation index by optical images, and for the development of allometric models to estimate mangrove biomass by SAR images.

The remote sensing in the study of Brazilian mangrove is still in development and there are many new perspectives to be explored. From those, we emphasize the use of freely available images of new sensors as OLI/Landsat, PANMUX and MUXCAM/CBERS-4, the use of very high resolution images for species mapping, hyperspectral data, SAR images to estimate aboveground biomass, and the application of quantitative techniques as OBIA, to map mangrove species and vegetation index to estimate green biomass. With respect to spatial resolution, which has changed a lot in these three decades, with the production of high and very resolution imagery, the studies of Brazilian mangroves by these tools showed an overall small growth and did not follow the global trend. However, we must consider that the advancement and consolidation of these tools in the context of Brazil, only will occur by the availability of cheaper and accessible images and greater availability of resources for acquiring them.

Finally, the diversity of remote sensing imagery combined with the freely availability of some images, as well a high variation on the longevity of the sensors, do not allow to conclude which is the best image to be used in the study and analysis of Brazilian mangroves. Thus, the selection of the appropriate images depends primarily on the scale and objectives of the study as well as the financial viability to acquire commercial satellite images. In this process, which is the first step in management studies that use these types of tools, is important to evaluate the potentialities and limitations of each type of images. Our study gives information and shows a framework to aid in this evaluation. Here we found that remote sensing and geoprocessesing are fundamental tools to be considered in mangrove and costal management.

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Appendix

Supporting Information associated with this article is available online at http://www.aprh.pt/rgci/pdf/rgci-662_Santos_Supporting-Information.pdf

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