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LONG-TERM EFFECTS OF OIL POLLUTION IN MANGROVE FORESTS (BAIXADA SANTISTA, SOUTHEAST BRAZIL) DETECTED USING A GIS-BASED MULTITEMPORAL ANALYSIS OF AERIAL PHOTOGRAPHS

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ABSTRACT

Oil spills are potential threats to the integrity of highly productive coastal wetlands, such as mangrove forests. In October 1983, a mangrove area of nearly 300 ha located on the southeastern coast of Brazil was impacted by a 3.5 million liter crude oil spill released by a broken pipeline. In order to assess the long-term effects of oil pollution on mangrove vegetation, we carried out a GIS-based multitemporal analysis of aerial photographs of the years 1962, 1994, 2000 and 2003. Photointerpretation, visual classification, class quantification, ground-truth and vegetation structure data were combined to evaluate the oil impact. Before the spill, the mangroves exhibited a homogeneous canopy and well-developed stands. More than ten years after the spill, the mangrove vegetation exhibited three distinct zones reflecting the long-term effects of the oil pollution. The most impacted zone (10.5 ha) presented dead trees, exposed substrate and recovering stands with reduced structural development. We suggest that the distinct impact and recovery zones reflect the spatial variability of oil removal rates in the mangrove forest. This study identifies the multitemporal analysis of aerial photographs as a useful tool for assessing a system's capacity for recovery and monitoring the long-term residual effects of pollutants on vegetation dynamics, thus giving support to mangrove forest management and conservation.

RESUMO

Vazamentos de petróleo são potenciais ameaças à integridade de ecossistemas costeiros. Em outubro de 1983, devido ao rompimento de um oleoduto, um manguezal com cerca de 300 ha, localizado na costa sudeste do Brasil foi impactado por 3.5 milhões de litros de petróleo. Visando avaliar os efeitos de longo prazo do petróleo sobre a vegetação do manguezal, foi realizada uma análise multitemporal (1962, 1994, 2000 e 2003) de fotografias aéreas em SIG. Fotointerpretação, classificação visual, quantificação de áreas, dados de campo e dados estruturais da vegetação foram utilizados na avaliação. Antes do vazamento, a vegetação exibia dossel homogêneo elevado desenvolvimento estrutural. Mais de dez anos após o derrame, a vegetação apresentou três zonas distintas, com diferentes impactos decorrentes do derrame de petróleo. A zona mais impactada (10.5 ha) apresentou árvores mortas, substrato exposto e bosques em recomposição com reduzido desenvolvimento estrutural. Os resultados indicam que os distintos impactos e recomposição refletem a variabilidade espacial da taxa de remoção do petróleo em cada zona do manguezal. A análise multitemporal de aerofotografias se revelou como útil ferramenta para avaliar a capacidade de recuperação da vegetação e monitorar os efeitos de longo prazo e residuais de poluentes, oferecendo subsídios à gestão e conservação dos manguezais.

Descriptors: Coastal wetland, Remote sensing, Impact assessment, Monitoring, Coastal management.
Descritores: Zona úmida costeira, Sensoriamento remoto, Avaliação de impacto, Monitoramento, Gestão costeira.

INTRODUCTION

Mangrove wetlands are tropical or subtropical intertidal forests composed of halotolerant plant species and are often located in the muddy, anoxic soils of estuaries, lagoons and river deltas (DAHDOUH-GUEBAS, 2002). As a coastal ecosystem, mangrove forests contribute to the long-term sustainability of more than one-third of the world's human population (BARBIER et al., 2008), fulfilling several important socio-economic and environmental functions. For example, mangroves support the conservation of biological diversity by providing habitats, spawning grounds, nurseries and nutrients for a number of animals, including many commercial species (FAO, 2007), and also protect coastal communities from rises in sea-level, storm surges and tsunamis (DAHDOUH-GUEBAS et al., 2005; MCLEOD; SALM, 2006; OLWIG et al., 2007).

Nevertheless, human activities along coastlines have dramatically reduced the world's mangrove areas (MARTINUZZI et al., 2009). Despite the degradation of mangrove forests' having been recurrently documented over time (DAHDOUH-GUEBAS; KOEDAM, 2008; ELLISON, 2008), direct and indirect anthropogenic pressures still do, unfortunately, persist (MOHAMED et al., 2009). In the proximity of large coastal cities, where mangroves usually occur, sources of hydrocarbons (from atmospheric deposition, shipping, oil spills or illegal oil-smuggling operations) highlight their vulnerability to oil pollution since mangrove sediments behave like a sink, retaining the toxicity of pollutants (BRITO et al., 2009).

On the southeastern coast of Brazil there are several sources of oil pollution, mainly in ports and oil terminals (RODRIGUES et al., 1999). The Baixada Santista Metropolitan Region in São Paulo state (Southeastern Brazil) is a densely urbanized region (CÉSAR et al., 2006) where the Port of Santos, the largest and fastest growing seaport in Brazil, situated on a sheltered, mangrove-lined estuary (POFFO et al., 2008), is located. It was in this region, on 14 October 1983, during the construction of a highway, that an approximately 20-ton rock fell onto a pipeline which broke and released about 3.5 million liters of crude oil. The oil drained from the land into the sea and affected some 10,000 ha of the coastal zone, impacting large areas of mangrove forests (SCHAEFFER-NOVELLI, 1986).

The sustainable use and management of mangrove forests cannot be undertaken without an understanding of the direct and indirect impact of human activities (DAHDOUH-GUEBAS, 2002). Thus it is that the use of aerial photographs and other remote sensing technologies in combination with geographic information systems (GIS) offers a useful tool for monitoring changes in mangrove forests (DAHDOUH-GUEBAS et al., 2002) and assessing anthropogenic impacts on them (CUNHA-LIGNON et al., 2009). Aerial photographs have been widely used in the mapping and assessment of mangrove forests (HEUMAN, 2011), allowing long-term decadal retrospection on the basis of spatio-temporal imagery analyses (DAHDOUH-GUEBAS et al., 2006).

For this study we carried out a GIS-based multitemporal analysis of aerial photographs of a mangrove area (Baixada Santista region, Brazil) which was severely impacted by the oil spill of 1983, in order to: (1) assess the long-term effects of oil pollution on the mangrove vegetation, (2) analyze mangrove stands' dynamics and their recovery after the oil spill, and also (3) offer the necessary elements for mangrove management and conservation, especially in the case of forests impacted by oil spills .

MATERIAL AND METHODS

Study Area

The Baixada Santista (24º50'S, 45º50'W) corresponds to the central segment of the São Paulo State coast, located in the Southeast of Brazil. This region presents a landscape greatly altered by human occupation in which chronic environmental conflicts with natural ecosystems have resulted from the pressures of rapidly expanding urban sprawl and industrial development (SANTOS et al., 2008).

Due to the 14 October 1983 oil spill which occurred in the Baixada Santista, about 3.5 million liters of crude oil drained from the land into the sea through the Bertioga Channel, one of the main water courses of this region. The mangrove study area selected (of about 300 ha) is located on the Iriri River, on the continental margin of the Bertioga Channel, Santos city, Baixada Santista, São Paulo State, Brazil (23º55'S, 46º13'W) (Fig. 1). This mangrove forest was severely impacted by the oil spill because it is situated near the area where the pipeline broke. The three typical mangrove species: *Rhizophora mangle* L. (Rhizophoraceae); *Laguncularia racemosa* (L.) Gaertn. F. (Combretaceae) and *Avicennia schaueriana* Stapf. & Leechman (Avicenniaceae) occur in the study area.

Remote Sensing and Geographic Information System

We first carried out a research aiming to find the available aerial photographs of the study area and found images from four years, 1962, 1994, 2000 and 2003 (Table 1),which were, therefore, the years chosen for this study. Then this time series of aerial photographs were processed using SPRING (Georeferenced Information Processing System) (CÂMARA et al., 1996), 4.3 edition, a free GIS software developed by the Brazilian National Institute for Space Research (INPE) that can be acquired on the SPRING[1]. SPRING is a second generation geographic database composed of Impima, Spring and Scarta applications.

The aerial photographs (1962, 1994) in analogical format were scanned with 600 dpi (dots per inch) of resolution and converted into digital format. The digital orthophoto (2000) was directly imported to Spring application and the other photographs were converted by grib extension into Impima, and afterwards imported into and georeferenced in Spring. Photointerpretation, visual classification, vector edition of polygons (classes of mangrove zones and their different features) and lines (mangrove forest drainage) and class area quantification were applied.

Classes of mangrove vegetation zones (inner, fringe and transition zones) and different features (gap, exposed substrate and patches of less dense canopy cover) were recognized using the visual criteria of photointerpretation: color, tonality, texture, shape and position (ecologically relevant location), based on the methodological use of the characteristic of air-borne imagery for mangrove forests (e.g. DAHDOUH-GUEBAS et al., 2006). Ground-truth and secondary data of mangrove vegetation structure were also used to verify the accuracy of the photointerpretations. In Scarta application, different layers were used to produce thematic maps of mangrove vegetation on the scales of 1:17,000, 1:9,000 and 1:4,000.

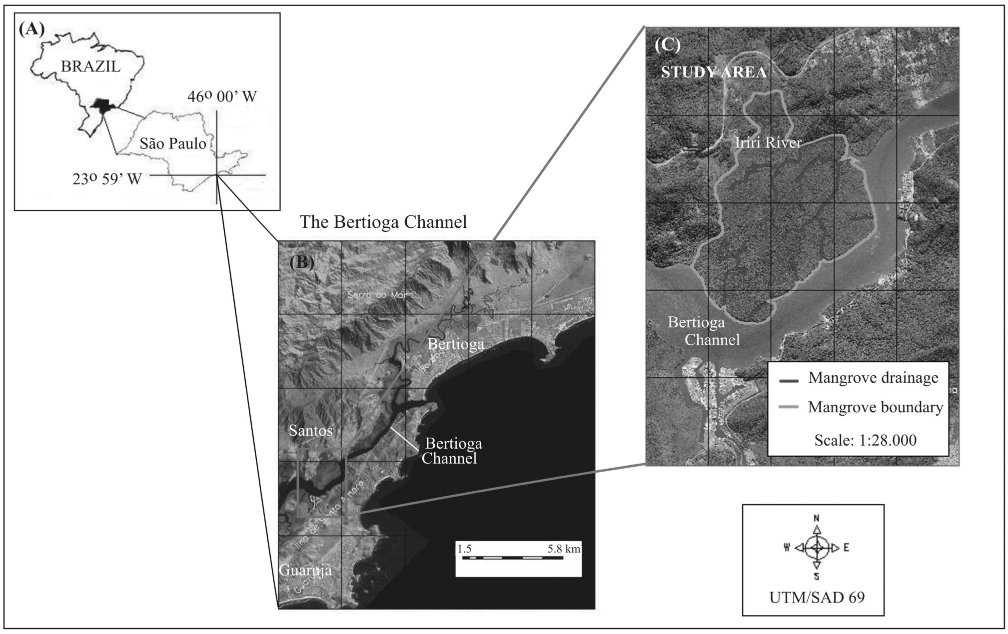

Fig. 1. The mangrove study area located in (A) Brazilian southeast, São Paulo State coastal zone, (B) Baixada Santista region, Bertioga Channel, (C) Iriri River.

Table 1. Features of aerial photographs used in this study, including type of material, year, scale, spatial resolution (pixel size) and data source.

Type of aerial photograph	Year	Scale	Spatial Resolution (m)	Source
Black-and-white	1962	1: 25 000	1.06	Laser/USP [a]
Black-and-white	1994	1: 25 000	1.06	Laser/USP
Digital colour orthophoto	2000	1: 30 000	1.00	IF [b]
Digital colour orthophoto	2003	1: 10 000	1.00	Funcate [c]

[a] Laser/USP: Laboratório de Aerofotogrametria e Sensoriamento Remoto, Departamento de Geografia, Universidade de São Paulo, Brazil.
[b] IF: Instituto Florestal do Estado de São Paulo, Brazil. [c] Funcate: Fundação de Ciência, Aplicações e Tecnologia Espaciais, Santos/SP, Brazil.

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[1] http://www.dpi.inpe.br/spring/english/index.html

Ground Truth and Vegetation Structure Data

A fieldwork expedition was undertaken in June 2007 to ground-truth the classification. A total of ten ground-truth points were sampled over the mangrove area. The geographical coordinates of each point were obtained using the GPS (Global Positioning System) and visual observations on mangrove species and those of associated trees, the presence or absence of gaps, seedlings and young and mature trees, using a specific table and ordinary photographs, were recorded. Vertical photographs of gaps in the mangrove canopy cover were taken using a digital camera on a support 0.90 cm above the mangrove substrate.

Secondary vegetation structure data of 1999, 2000, 2002, 2003 and 2004 of the mangrove transition zone[2] (e.g., FIRME et al., 2004) were used to assist in the photointerpretation of the changes in mangrove vegetation cover. The vegetation structure data were collected and analyzed in accordance with CINTRÓN and SCHAEFFER-NOVELLI (1984). Two fixed plots were delimited: P1- a recovered stand with little oil remaining in the sediment and P2- a recovered stand with a great amount of oil remaining in the sediment. The plot size varied between 5x2.5 m (12.5 m^2) and 10x10 m (100 m^2). The plant species identified in each plot, their height and DBH (diameter at or close to 1.30m from the ground) were recorded. Vegetation structure parameters, the mean diameter of the stand and its relative density and mean height were calculated using Excel software.

RESULTS

Mangrove Stands Before the Oil Spill in 1962

Twenty-one years before the oil spill (1962), the mangrove canopy cover exhibited two zones: fringe and inner (Fig. 2). Both zones presented a homogeneous dark grey tonality which may well indicate stands of homogeneous canopy cover without any spaces between them. The fringe zone corresponded to the mangrove area located along and close to creeks (Fig. 2), occupied almost 58% of the total mangrove area (Table 2), exhibited a coarse grain texture and presented no different features. The coarse texture in this zone may indicate the particular composition and arrangement of tree canopies in stands located along and close to creeks.

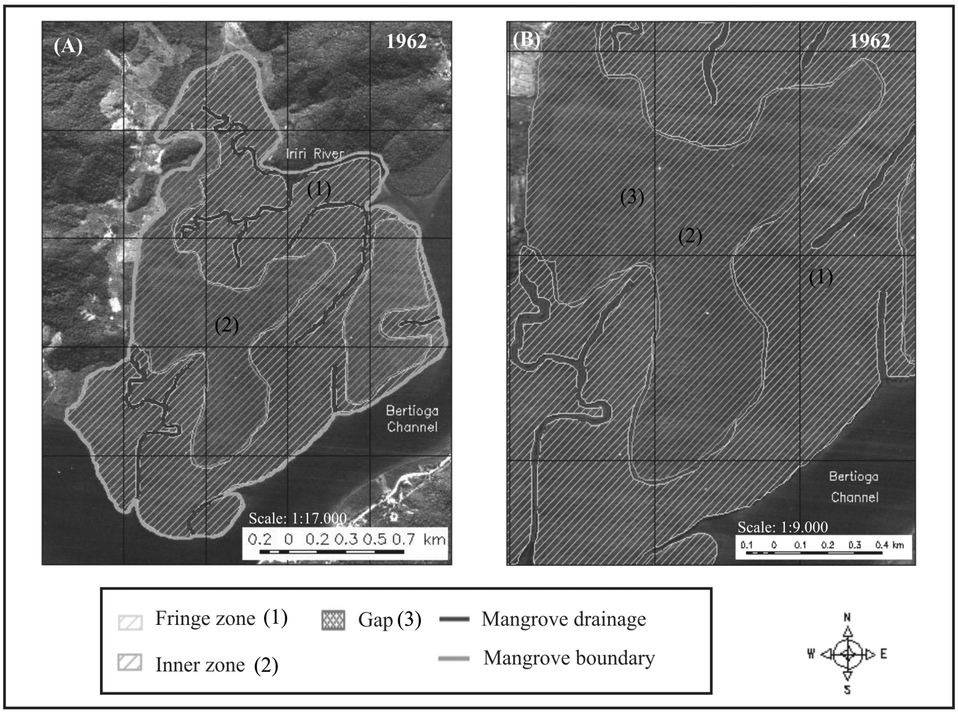

Fig. 2. Visual classification of the (A) study site and (B) different features presented in the mangrove inner zone in 1962.

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[2] The vegetation structure data were collected and processed by post-graduate students of the discipline IOB-5721 (O ambiente biológico dos manguezais); supervised by Prof. Dr. Yara Schaeffer-Novelli (Departamento de Oceanografia Biológica, Instituto Oceanográfico, Universidade de São Paulo, Brasil). These data were collected in the mangrove transition zone which corresponds to a mangrove area located landward in the transition to terrestrial vegetation.

Table 2. Area of each mangrove zone classified and its relation (as a percentage) to the total mangrove area on the Iriri River, Bertioga Channel, Baixada Santista, SP, Brazil.

Year	1962		1994		2000		2003	
Mangrove zone	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%
Fringe	153.70	58.00	203.80	68.10	205.10	67.70	205.90	67.80
Inner	111.20	42.00	84.81	28.40	92.10	30.40	92.40	30.40
Transition	-	-	10.52	3.50	5.82	1.90	5.24	1.80
Total area	264.90		299.10		303.00		303.50	

The inner zone corresponded to the central and landward region of the mangrove forest (Fig. 2), presented medium grain texture and occupied approximately 42% of the total mangrove area (Table 2). Elements exhibiting a circular shape and dark tonality, giving the impression of a hole, were recognized in the continuous mangrove cover (Fig. 2). Based on ground-truth data this contrasting feature was identified as a gap in the mangrove canopy cover. In 1962, gaps occurred in reduced number (Table 3) and were similar in size and shape. These results show that, before the oil spill, the mangrove zones exhibited a homogeneous, dense canopy cover that might well indicate well-developed stands.

Mangrove Stands After the Oil Spill: 1994, 2000 and 2003

More than eleven years after the oil spill, the mangrove cover exhibited three distinct zones: fringe, inner and transition (Fig. 3), each showing different image characteristics and features over the years analyzed (Table 4).

Table 3**.** Different features classified by photointerpretation as typical of the (A) inner and (B) transition zones of the Iriri River mangrove forest, Bertioga Channel, Baixada Santista, SP, Brazil.

(A) Inner zone	Year			
	1962	1994	2000	2003
Number of gaps	4	33	48	55
Patch of less dense canopy (ha)	-	1.90	1.79	1.56
(B) Transition zone	Year			
	1962	1994	2000	2003
Number of gaps	-	4	4	2
Exposed sediment (ha)	-	0.34	0.19	0.06

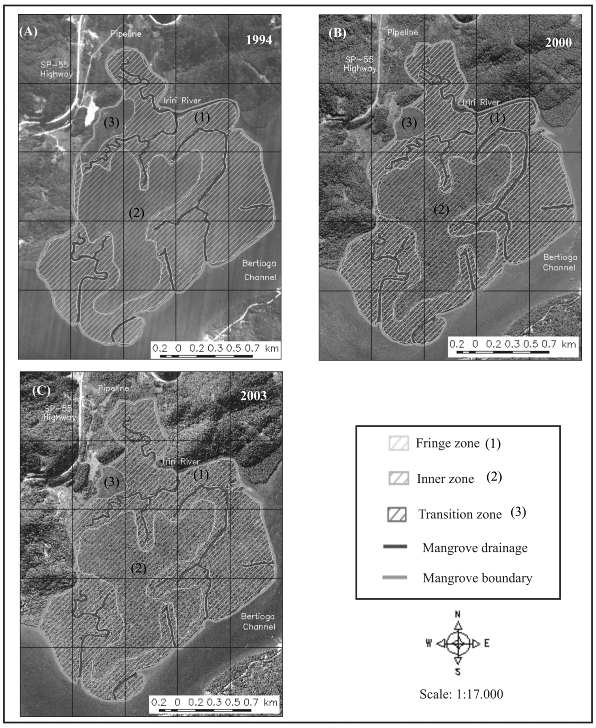

Fig. 3. Visual classification of the study site in (A) 1994 (B) 2000 and (C) 2003.

Table 4**.** Summary of photointerpretation including image characteristics of position, tonality/color and texture for each mangrove zone on the Iriri River, Bertioga Channel, Baixada Santista, SP, Brazil.

Year	Mangrove zone	Position	Tonality/color	Texture
1962	Fringe	Along and closely of creeks	Dark gray	Coarse grain
	Inner	Central and landward back region	Dark gray	Medium grain
1994	Fringe	Along and closely of creeks	Intermediate to light grey	Coarse to medium grain
	Inner	Central region	Dark gray	Medium grain
	Transition	Landward back region	Light gray	Fine grain
2000	Fringe	Along and closely of creeks	Intermediate to light green	Coarse to medium grain
	Inner	Central region	Dark green	Medium grain
	Transition	Landward back region	Light green	Fine grain
2003	Fringe	Along and closely of creeks	Intermediate to light green	Coarse to medium grain
	Inner	Central region	Dark green	Medium grain
	Transition	Landward back region	Light to intermediate green	Fine to medium grain

Fringe Zone

After the oil spill, the fringe zone (Fig. 3) exhibited coarse to medium grain texture and a discontinuous canopy cover in which tree crowns were individually visualized. This zone occupied about 68% of the mangrove area from 1994 to 2003 (Table 2). Gaps did not occur in all the years (Table 3). The changes of image characteristics from dark grey tonality and coarse texture (1962) to light tonality (1994), intermediate and light color (2000, 2003) and medium texture (1994, 2000, 2003) may well indicate the discontinuous canopy cover observed after the oil spill (Table 4).

Mature specimens of *R. mangle*, *L. racemosa* and *A. schaueriana* showing crowns arranged with spaces between them and numerous seedlings of *L. racemosa* and *R. mangle* covering the mangrove sediment were observed in this zone during the fieldwork carried out in 2007.

Inner Zone

The inner zone, located in the central region of the mangrove forest (Fig. 3), exhibited medium grain texture, numerous gaps and one patch of less dense canopy cover (Fig. 4). The mangrove canopy cover was characterized by tree crowns which were not individually visible. This zone occupied roughly 30% of the mangrove area from 1994 to 2003 (Table 2).

During nine years (1994-2003), the number of gaps increased (Table 3). In the fieldwork (2007) we discovered gaps in two different recovery phases, based on the model proposed by DUKE (2001). The gaps in the recruitment phase exhibited maximal opening, early recruitment of young seedlings, exposed sediment and advanced degradation of dead trees, which were reduced to standing stumps, branches and stems (Fig. 5). The gaps in the filling phase exhibited smaller openings than the gaps in the recruitment phase and the presence of young recruits covering the sediment (Fig. 5).

The patch of less dense canopy cover (Fig. 4) occurred as a different element in the mangrove canopy and exhibited elliptic shape, discontinuous canopy cover and visible sediment between trees. The tonality of this patch was light grey (1994) and light green (2000 and 2003) and the area occupied decreased over the years (Table 3). During the fieldwork (2007) this area exhibited high microtopography, mature trees lower than the surrounding ones and the presence of *L. racemosa* seedlings and shrubs of *Acrostichum aureum.*

Transition Zone

When the classification of 1962 (Fig. 2) is compared with those made after the oil spill (Fig. 3), it reveals the presence of a transitional zone which exhibited different image characteristics (Table 4) and features (Table 3). This zone corresponded to a basin within the more landward area of the mangrove forest, with a transition to terrestrial vegetation (Figs 3 and 6) and which occupied about 2% to 3% of the mangrove area (Table 2).

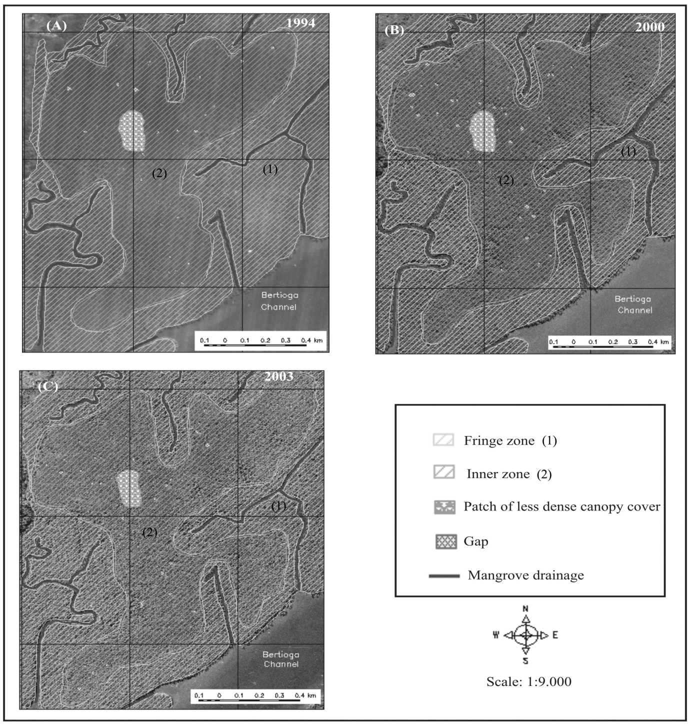

Fig. 4. Visual classification of different features presented in the mangrove inner zone in (A) 1994, (B) 2000 and (C) 2003.

Fig. 5. Features of gaps in different recovery phases. Recruitment phase: (A) vertical photograph of the gap showing the maximal opening, (B) exposed sediment and few early young seedlings and, (C, D) advanced degradation of dead trees. Filling phase: (E) vertical photograph of the gap showing a small opening and (F) the presence of young recruits largely covering the sediment of the gap (fieldwork, 2007).

From 1962 to 1994 the area (inner zone) occupied by the transition zone presented a change from medium grain texture and dark grey tonality to a fine texture and light grey tonality (Table 4, Figs 2 and 3). These changes may indicate that well-developed stands (1962) had been replaced by stands with reduced structural development (1994 to 2003), as was in fact confirmed by the vegetation structure data of 1999 to 2004 (Fig. 7).

In 1990, seven years after the oil spill, during a previous inspection of the transition zone, we had been able to confirm the first evidences of the recovery of the vegetation. This was characterized by young specimens of *L. racemosa* replacing a well-developed stand which had been dominated by mature *R. mangle* trees which exhibited elevated mortality due to the large amount of oil in the mangrove sediment. Moreover, prior to 2005, when we paid our last visit of inspection to this area, we had observed the presence of oil in the sediment of this zone and the mangrove vegetation of low trees of reduced diameter and canopies.

The vegetation structure data of 1999 to 2004 indicated that the mangrove stands in this zone were characterized by low mean diameter (<4.85 cm), low mean height (<5.9 m) and high relative density of trees, mainly *L. racemosa,* with DBH of between 10 and 2.5 cm and even less than 2.5 cm (Fig. 7). Between 2002 and 2004 the mean DBH and height of the stands showed an overall tendency to increase while the density of trees with DBH of less than 2.5 cm decreased, indicating some increase in the mangroves' structural development. Therefore, the changes observed in the image attributes between 2000 and 2003 (Table 4) probably also indicate the changes which occurred in the vegetation structure from 2002 to 2004 (Fig. 7).

Moreover, the transition zone presented areas of exposed substrate (Fig. 6) which may have arisen as a result of the high mortality of trees caused by the acute effects of the oil pollution. A decrease in the area of exposed substrate over the years (Table 3) might indicate the recovery process of these mangrove stands. Additionally, gaps (Fig. 6) occurred in smaller numbers and decreased with time (Table 3), which could indicate an advanced stage of the recovery of the gaps.

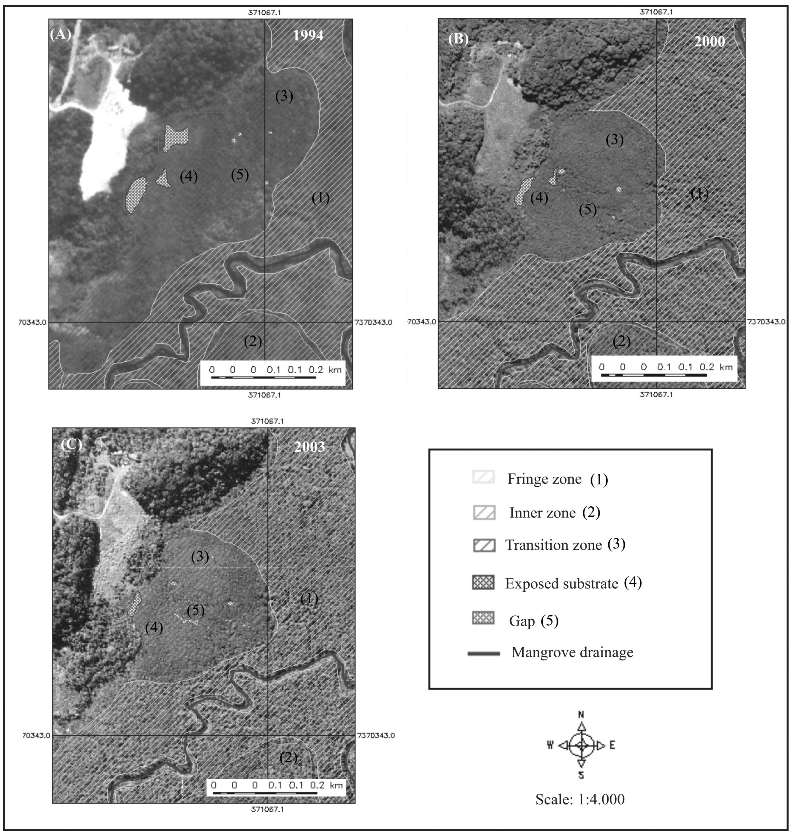

Fig. 6. Visual classification of different features presented in the mangrove transition zone in (A) 1994, (B) 2000 and (C) 2003.

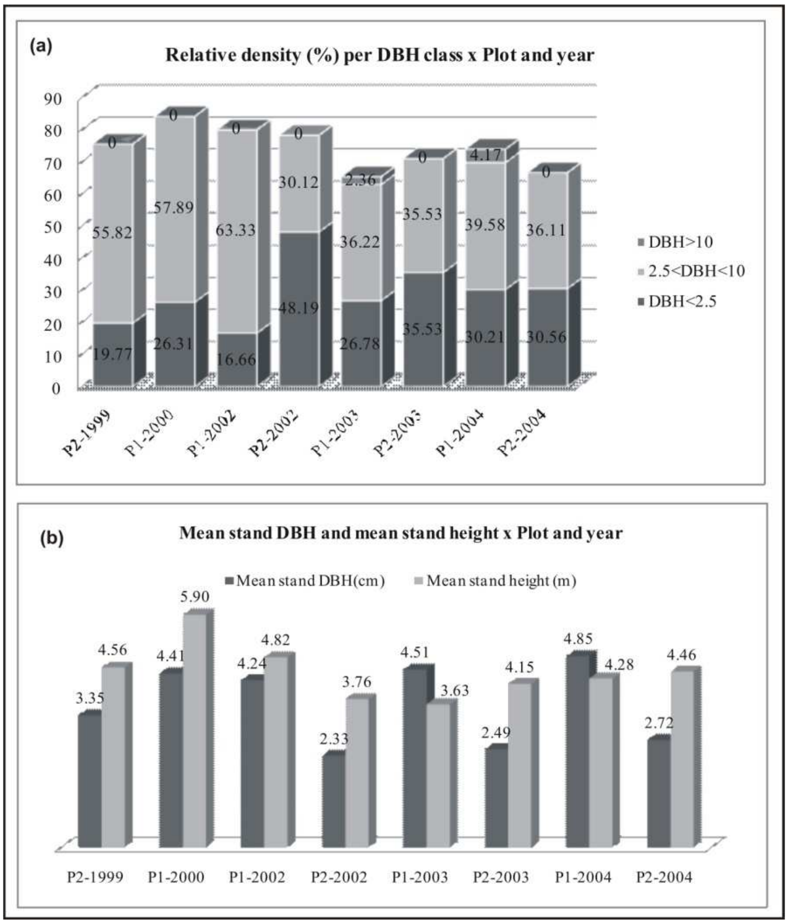

Fig. 7. Secondary vegetation structure data of mangrove stands located in the transition zone (FIRME et al., 2004). (A) Mean diameter stand (DBH) and mean height stand per year and plot. (B) Relative density (%) of DBH classes per year and plot. (P1- plot 1, P2- plot 2).

DISCUSSION

Long-term Effects of Oil Pollution on Mangrove Zones

The present study reveals that each mangrove zone presented different image characteristics (Table 4), features (Table 3) and spatio-temporal changes over the period of 41 years (1962-2003) (Figures 2 and 3). These changes reflect the spatial heterogeneity caused by the small-scale effects of the oil pollution on the mangrove zones, as well as indicating that recovery and gap regeneration processes have occurred in this impacted mangrove area. Mangroves are resilient and recover quickly when given an opportunity and if the geomorphological and hydrological features of their habitat are not changed by human use (MARTINUZZI et al., 2009).

According to the conceptual model for evaluating residence time of oil in mangrove forests (JACOBI; SCHAEFFER-NOVELLI, 1990), after a spill on a mangrove coastline the oil tends to be retained by the mangrove sediment, thus its removal occurs mainly in association with seaward particle export. Since the export of detritus depends on tidal flow, the area affected by an oil spill can be divided into sections parallel to the coastline which present different oil removal rates which increase seaward (JACOBI; SCHAEFFER-NOVELLI, 1990). Based on this model, we suggest that the distinct spatio-temporal changes and long-term effects of oil pollution on the mangrove study area occur by virtue of the different oil removal rates in each mangrove zone.

Thus, the fringe zone (Fig. 3, Table 4), which corresponds to an area of freely flowing water and is thus washed constantly even by the lowest tide, showed a high oil removal rate, since the oil was exported by the daily tidal flow. Therefore, the effects of oil pollution in this area have been weak, indicating that it was the least impacted mangrove zone. Discontinuous canopy cover was observed after the oil spill in this zone and may evidence a long-term effect of oil pollution on the mangrove vegetation cover. The discontinuous canopy might have resulted from the death of a few trees or from the defoliation and reduction of leaf production of the surviving trees. DUKE et al. (1997) suggested that an unusually “open” canopy was possibly due to sublethal damage to surviving mangrove forests impacted by oil spills.

By contrast, the inner zone (Fig. 3, Table 4) is a region of limited water circulation, washed only by medium and high tides and which consequently showed an intermediate oil removal rate, thus constituting the moderately impacted mangrove zone. An increase in the number of gaps was the most evident feature observed after the oil spill (Table 3) and may indicate a long-term effect of oil pollution as, on the other hand, the process of gap regeneration may be seen as a strategy for mangrove recovery after oil spills.

Gaps in mature mangrove forests affected by oil spills were also detected by DUKE et al. (1997, 1999). While lightning seems a likely common cause of small gaps in mangrove forests, pollutants are another possible cause (DUKE, 2001). Canopy gaps drive the gap phase regenerative cycles in mangrove forests (CLARKE; KERRIGAN, 2000; DUKE, 2001; IMAI et al., 2006; LÓPEZ-HOFFMAN et al., 2007), and provide the adaptive mechanism that "resets" stands to new conditions and confers stability and permanence to the system (SCHAEFFER-NOVELLI et al., 2005). Thus, the normal gap recovery process presumably also acts as an attempt to repair the oil damage and operate in the post-spill recovery of mangrove forests (DUKE et al., 1999). However, it is difficult to understand how this turnover strategy alone might promote stand longevity, especially where stands have been deforested by oil spills (DUKE et al., 1997).

Finally, the transition zone which is located landward, at the back of the mangrove forest (Figures 3 and 6), is washed only by the highest tides, thus characterizing a still-water region. For this reason, this zone showed a reduced oil removal rate as the oil tended to remain in the sediment. Consequently, this area was the most severely impacted mangrove zone where well-developed stands dominated by *R. mangle* were replaced by stands of *L. racemosa* with reduced structural development.

Our results are in agreement with those of studies by DUKE et al. (1997, 1999) who ascertained that in mangrove forests impacted by oil, the most seriously affected areas were the low to mid-intertidal zones. These areas presented regenerated gaps with high densities of low trees and increased oil concentrations in the mangrove sediment (DUKE et al., 1999). The characteristics of the substrate and seasonal variations in hydrodynamics can contribute to the persistence of oil on or inside the sediments, thus increasing its environmental impact (GARRITY et al., 1994; BURNS; CODI, 1998). In such situations, it is to be expected that recovery should be retarded (DUKE et al., 1999) and long drawn-out (up to 50 years), or that the damage should be definitive (BRITO et al., 2009).

Recovery by stands with reduced structural development may, therefore, indicate a long-term effect of oil pollution in mangrove forests. It appears that the oil which remained in the sediment of the transition zone of the study area has been acting as a stressor, draining energy from the mangrove stands that could otherwise be allocated to increasing the vegetation structure, thus generating stands with reduced structural development.

Application of Multitemporal Tools for Mangrove Conservation and Management

Understanding vegetation dynamics is important for conservation, restoration and sustainable exploitation purposes. Information on mangrove dynamics serves as a basis for deciding whether or not human interference in the form of management or restoration is appropriate (DAHDOUH-GUEBAS et al., 2004). In this view, it is important to be aware of natural processes and how they might have been altered, if at all, by oil spills. Otherwise, the outcome of the good intentions implicit in projects of habitat restoration could result in further destruction of this already disrupted and fragile habitat (DUKE et al., 1999).

In this study, the GIS multitemporal analysis of aerial photographs proved to be a useful tool for assessing a system’s recovery capacity (ecological resilience), how fast the system returns to its earlier state (engineering resilience), as well as for monitoring long-term residual effects of oil pollution on mangrove forests, offering information about vegetation and gap dynamics. This type of information has significant implications for future restoration projects which call for the evaluation of long-term site stability (DUKE et al., 1997).

Therefore, the analysis of aerial photographs continues to be an important tool for assessing forest dynamics and monitoring natural and man-made changes, as well as providing low cost, large-scale and spatial-temporal information on the period prior to that of the data available from field surveys (CUNHA-LIGNON et al., 2009). Moreover, nowadays the easy availability of geoprocessing software, such as the Brazilian GIS SPRING, makes it possible to carry out GIS-based studies for conservation and management purposes at very low cost, highlighting the potential of combining remote sensing and GIS tools.

In this approach, it is crucial to bear in mind that study accuracy is directly dependent on the interpretative skills of both analyst and user, as well as on the conceptual framework used in the analysis (SCHAEFFER-NOVELLI et al., 2008) to obtain the practical information necessary for conservation and management purposes. The improvement of the management tools available for the restoration of lost mangroves forests would benefit from a better understanding of how population and human activities influence the conservation of these habitats (MARTINUZZI et al., 2009).

CONCLUSION

Based on multitemporal analysis and field studies, we identified three zones of mangrove canopy cover reflecting distinct long-term residual effects of oil pollution, vegetation recovery and gap creation and regeneration over 41 years (1962-2003). Although the mangrove stands showed themselves capable of recovering from an oil spill, the recovery time was very long, more than seven years, and the recovered stands presented reduced structural development and different species composition. Moreover, recovery depends on the tidal flushing which removes the oil from the environment. Hence, mangrove forests located further inland and in regions with restricted water flow are the most severely impacted by oil spills. Further, as the oil remains in the sediment, it acts as a stressor, reducing stand structural development.

Our results indicate that a time series of aerial photographs and GIS are practical tools for addressing direct conservation threats and assessing environmental impacts on mangrove forests, providing the technical elements necessary for future development and the establishment of the policies necessary for the conservation of the coastal and marine landscape and for resource management.

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