SPATIAL ANALYSIS FRAMEWORK FOR MANGROVE FOREST RESTORATION: A THEORETICAL CASE FOR ITAIPU LAGOON, BRAZIL

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ABSTRACT

Mangroves are coastal ecosystems in transition between sea and land, found worldwide in tropical and subtropical regions. Due to the recognition of the importance of mangroves, new restoration methods are being studied. Our objective is to develop a methodology that selects the most appropriate places for planting the species *Rhizophora mangle*. The methodology consists of the spatialization and overlay of three variables in a Geographic Information System. Three abiotic factors restricted to the intertidal zone that influence the development of *R. mangle* were used: interstitial water salinity, organic matter content and sediment type. Around the lagoon, 18 field stations were established to collect samples for the three abiotic factors. The sample data were interpolated for the whole area of interest, *i.e.* the intertidal zone of the lagoon, because this is the preferential habitat of *R. mangle*. Itaipu Lagoon was chosen for the development our model because it is an area where a natural expansion of the mangrove trees and recent efforts of planting *R. mangle* take place. This methodology offers an estimate of cost and total number of propagules that could be planted, and it indicates more favorable areas for the development of the species.

Keywords: *Rhizophora mangle,* red mangrove, wetland, restoration, GIS, geoprocessing.

RESUMO

O manguezal é um ecossistema litorâneo de transição entre a terra e o mar, localizado mudialmente nas regiões tropicais e subtropicais. Devido ao reconhecimento da importância dos mangues, novos métodos de restauração estão sendo estudados. Para tanto, o nosso objetivo é desenvolver uma metodologia que selecione os locais mais adequados para o plantio da espécie *Rhizophora mangle*. A Laguna de Itaipu foi a área escolhida, pois é uma região onde existe uma expansão natural dos mangues e recentes esforços de plantio de *R. mangle* vem ocorrendo. A metodologia consiste na espacialização (interpolação) e sobreposição (overlay) de três fatores abióticos em Sistemas de Informações Geográficas que influenciam no desenvolvimento da espécie *R. mangle*. Os fatores estudados são: salinidade da água intersticial, percentagem de matéria orgânica no solo, e o tipo de sedimento, analisados na zona intertidal. Ao redor da laguna foram coletados 18 amostras no campo e interpoladas para toda a área de interesse. Esta metodologia oferece uma indicação das áreas mais propícias para o plantio da espécie *R. mangle* bem como uma estimativa de custo e do número total de propágulos a serem plantados.

Palavras-chave: *Rhizophora mangle,* mangue vermelho, áreas alagadas, restauração, SIG, geoprocessamento.

INTRODUCTION

Mangrove forests are coastal ecosystems in transition between sea and land, found worldwide in tropical and subtropical regions (GIRI et al., 2011). Mangrove vegetation may take the form of trees, shrubs, palms or ground ferns, normally growing above mean sea level in the intertidal zone of marine coastal environments or estuarine margins (DUKE, 2006). The influence of environmental factors and their fluctuations on the coastline determines strong natural selection on species, few of which are adapted to tolerate extremes of water salinity, winds, solar radiation, drought and flooding, amongst other factors (VANNUCCI, 2001). These extremes environmental conditions that determine the low biodiversity compared to the rain forest (VANNUCCI, 2001; RICKLEFS & LATHAM, 1993). In Brazil, mangroves are present along most of its coastline, from the north, at Oiapoque river in Amapá (4° 30' N) to Laguna, in Santa Catarina (28° 30' S) (SCHAEFFER-NOVELLI et al., 1990; SPALDING et al., 1997), its southern most limit.

Mangroves provide a nursery environment offering protection and refuge for juvenile fish against piscivores (LAEGDSGAARD and JOHNSON, 2001; WORM et al., 2008). Therefore, mangroves are important in increasing fishery production (ABURTO-OROPEZA et al., 2008; SANTOS et al., 2016) and protection of the coastal areas from natural disasters, for instance, tsunamis, storms and others (DAHDOUH-GUEBAS et al., 2005b). Estimates suggest that mangroves provide more than USD 1.6 billion annually in ecosystem services (COSTANZA et al., 1997).

Aburto-Oropeza et al. (2008) showed that in the Gulf of California, fisheries landings are positively related to the local abundance of mangroves. For this reason, these authors estimated an annual economic median value of fisheries in USD 37,500 per hectare of mangrove, which increased the economic value of the worldwide services of mangroves. For these and other reasons, mangroves exert an important socio-economical role (BISWAS et al., 2009; BARBIER, 2007; DAHDOUH-GUEBAS et al., 2000; DAHDOUH-GUEBAS, 2013).

At least 35% of the world's mangroves have been lost, exceeding losses for tropical rain forests and coral reefs (VALIELA et al., 2001). In Brazil, at least 50,000 hectares of mangrove forests were lost mostly along the southern coast (FAO, 2005). According to the Food and Agriculture Organization (FAO, 2007) if deforestation of mangroves continues, it could lead to severe loss of biodiversity and livelihoods, possibly to a world without mangroves (DUKE et al., 2007).

Due to the conversion of mangrove forest into others uses, studies on the restoration of mangroves have been performed (BISWAS et al., 2009; BOSIRE et al., 2008a, 2008b, 2006, 2005a, 2005b, 2004, 2003; KAIRO et al., 2001; WALTERS, 2008, 2000). Mangrove restoration implies the generation of many social and environmental benefits, because they include a great potential increase of natural resources. For instance, the promotion of jobs for the local population, protection for the fragile tropical estuaries and an enhancement of local biodiversity (IFTEKHAR and TAKAMA, 2008; KAIRO et al., 2001). Environmental restoration is the return of a degraded environment site to its original state or close to it (FIELD, 1999). Studies on restoration of mangroves assume that flooded areas are adapted to stressful environments and are relatively susceptible to restoration efforts (TWILLEY, 1998). Restoration of mangroves has succeeded in many locations in Brazil (MOSCATELLI, 2003).

However, to select ideal sites for planting, one needs a good understanding of the niche of the concerned species. The ecological niche describes the limits of environmental conditions that a species needs to grow and develop (HUTCHINSON, 1957). When the environment does not limit the distribution of certain species, the effects of environmental extremes can suppress the structural development of mangroves and reduce their structural complexity (POOL et al., 1977). Rabinowitz (1978) in her study found that each mangrove tree species has its rate of tolerance to environmental variables and concluded that the zonation of mangroves is related to the physiological preferences of each species. Environmental factors influence the structure, function of mangrove forests varying according to different scales, such as; global, regional and local (DUKE et al., 1998).

A method integrating Geographical Information Systems (GIS) and geoprocessing has been developed to choose priority areas for reforestation (ARCOVERDE et al., 2011). GIS provide a very effective tool in habitat analysis and ecological restoration, namely by using geospatially identified criteria values and by modelling ideal sites for planting based on suitability maps (ROISE et al., 2004).

In 2001, the proposed framework was published in the V Brazilian Ecology Conference (XIMENES and GONDIN, 2001) and in parallel, Dahdouh-Guebas and Koedam (2002) proposed a complex methodology using a combination of remote sensing, fieldwork and GIS to do what they termed ‘map-based regeneration’. However, adopting a less complex theoretical framework proposed by Dahdouh-Guebas and Koedam (2002), the present study is the first to actually apply this.

For this study, we selected the Red mangrove (*Rhizophora mangle* L.), because there are numerous studies about its biology, and because it has been widely used in local mangrove restoration projects (MOSCATELLI, 2003). The variables selected are those that are known to influence the zonation of *R. mangle.* We used the scientific literature to select important environmental variables that determine the local distribution of *R. mangle* in estuaries, mainly in the Americas. In this way, the three environmental variables analyzed were: sediment type, soil organic matter content, salinity of interstitial water, all circumscribed to the areal extent covered by the intertidal zone. From the literature studied, we identified ranges, which seem to be the most favourable for the occurrence of *R. mangle*.

The goal of this study is hence to propose a framework based on GIS and geoprocessing tools for selecting sites suitable for mangrove restoration.

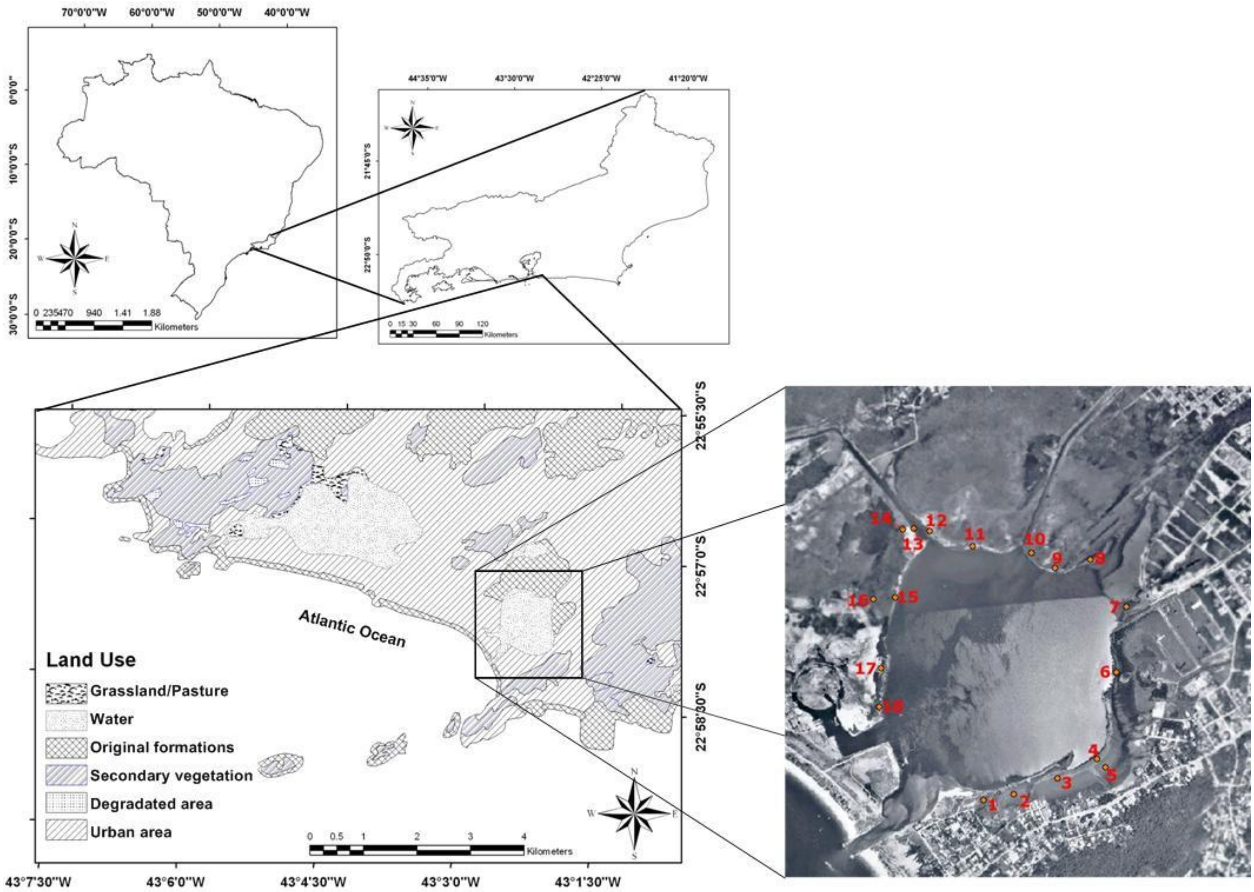
STUDY AREA

Itaipu lagoon is part of the Piratininga-Itaipu lagoon system, and it is situated in Niterói city, state of Rio de Janeiro, Brazil, between longitudes 043°06’W and 043°02’W and latitudes 22° 58’ S and 22° 56’ S (Fig. 1). Itaipu Lagoon is also part of the Parque Estadual da Serra da Tiririca that was created by state decree 1.901 of November 29, 1991.

According to the Köppen-Geiger climate classification the local is type Aw (KOTTEK et al., 2006), with a rainy season in the summer and a dry winter. Average annual temperature is 24°C and the average annual precipitation is ca. 1300 mm (BARROSO et al., 1994). Itaipu Lagoon has a circular shape with 2 km^2 of area, and an average of 1.2 m depth. It receives waters from a 23 km^2 watershed (KNOPPERS et al., 1999) via the rivers João Mendes, Vala and Valão of Itacoatiara watershed. The main freshwater contributor is the João Mendes river with 0.10 $m^3 s^{-1}$ from a 16.8 km^2 watershed (KNOPPERS et al., 1999). Up to the 1970’s Itaipu had only occasional exchange with the sea through a natural canal opened during heavy rainfalls, when the combination of the lagoon’s significantly higher water level and high tide conditions caused a breach on the beach sandbar allowing influx of seawater and drainage of accumulated fresh water (LAVENÈRE-WANDERLEY and SILVA, 2000).

In 1979, a breakwater was built to ensure permanent communication between the sea and the lagoon. For this, a 15 meter wide canal was dredged open (FEEMA, 1988). Since then, the arrival of halophytes has occurred naturally and a few mangrove trees on the western flank of the lagoon have been established due to proper conditions for development, which include brackish water and reducing soils. Also, others have been established in the northeastern margin of the lagoon which is characterized by fine sediments and a high percentage of humid and organic soils (ECP, 1979; IBAMA, 1998; BARROSO et al., 1994). Since 2000, a local Non-Governmental Organization (NGO) has attempted to plant red mangrove propagules on the southwestern flank (FONSECA and DRUMMOND, 2003). Also, local volunteering efforts since 2012 has resulted in over two thousand red mangrove seedlings in a 2 ha in the lagoon’s perimeter (REDAÇÃO NACIONAL, 2014).

Figure 1. Map and aerial photograph of 1996 showing location of 18 sampling stations in Itaipu Lagoon, Niterói, Brazil.



Fonte: Photo courtesy of CIDE (1996) Foundation and IBGE land use map.

MATERIALS AND METHODS

The intertidal zone being our area of interest, we estimated its area through visual interpretation of the aerial photograph and local observations (Fig. 1). The aerial photograph supplied by CIDE Foundation (1996) on a 1:8000 scale was scanned and ten ground control points (GCP) were established in the field using a Garmin Global Positioning System (GPS) III Plus. Other 20 GCPs were acquired from a local admiralty chart of Guanabara Bay in order to georeference the image using UTM projection and Datum SAD-69. The main software used in this study was IDRISI 32 developed by Clark University (EASTMAN, 1997).

Eighteen field stations in the intertidal zone spread along the perimeter of Itaipu Lagoon were established (Fig. 1). In each station, sediment and interstitial water samples were collected.

The interstitial water was collected *in situ*, from holes dug 30 cm deep with a spade. Once the hole was filled with interstitial water, according to the method described in Schaeffer-Novelli and Cintrón (1986) a water sample was collected. Interstitial water salinity was measured using a portable Bio-Marine Aquafauna salinity refractometer with a ± 1 Practical Salinity Unit (PSU) accuracy. All data for this study were gathered between October 2000 and October 2001.

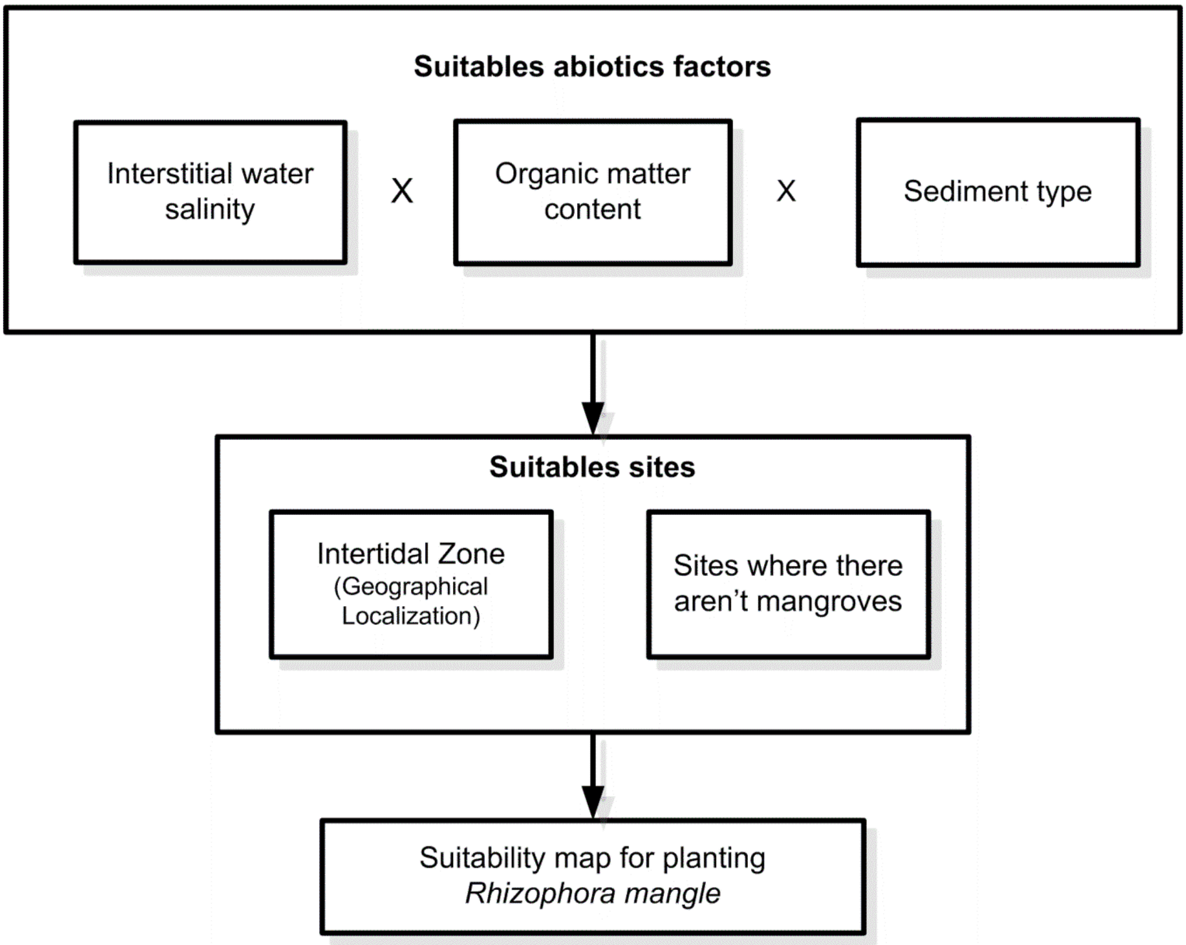
The soil samples in each station were collected and kept refrigerated in styrofoam boxes until arrival at Universidade Santa Úrsula's chemical oceanography laboratory. The method described in Suguio (1973) was used to analyze the sediment types and organic matter content. The sediment types were classified according to Wentworth (1992).

Finally, we used two high-resolution images available on Google Earth from 2003 and 2012, so as, to verify if the proposed methodology provided a satisfactory prediction of where planting efforts were appropriate. This being said, we recall that Lewis and Marshall (1997), Stevenson et al. (1999) and finally Bosire et al. (2008) suggested an actual (costly) planting activity only after attempts were made to restore natural hydrology.

The environmental variable results for the 18 stations were interpolated in order to develop three thematic layers using the nearest neighbour method. In this way, the values of sediment types, organic matter content and interstitial water salinity, were estimated over the total intertidal zone perimeter of Itaipu Lagoon. Subsequently the interpolated image was reclassified using the suitability ranges in Table1. A constraint mask was used to exclude all values outside the intertidal zone.

The Boolean algebra tool in the GIS was used to select suitable areas for planting red mangrove. In a Boolean image, the zero value indicates areas that do not fulfil the desired condition, while the value of 1 indicates a positive condition. Using values of zero and one, logical operations may be performed between multiple layers (EASTMAN, 1997). Figure 2 shows the procedure for the proposed framework. The layers were multiplied by Boolean operation then only the suitable condition was retained. Moreover, this study has only considered places that did not have mangrove vegetation at the period of this study in 2001.

Figure 2. Framework for the selection of suitable sites for planting *Rhizophora mangle.*



We defined criteria for selecting suitable areas for planting of red mangrove based on a careful review of the scientific literature that describes characteristics of red mangrove sites (Table 1).

Table 1. Environmental parameter ranges of values selected for the planting of red mangrove (*R. mangle*).

Variables	Range	References
SEDIMENT TYPE	< 125 µm Silt/Clay and Very fine sand	CARMO ; 1998, CINTRÓN and SCHAEFFER-NOVELLI, 1983, LOURO et al., 1994, CHEN and TWILLEY, 1998.
SOIL ORGANIC MATTER CONTENT	> 100 g/kg	CARMO, 1998 ; CINTRÓN and SCHAEFFER-NOVELLI, 1983 ; LOURO et al., 1994; TWILLEY et al., 1995; TOMLINSON, 1986.
INTERSTITIAL WATER SALINITY	> 25 PSU < 55 PSU	SOTO and JIMENÉZ, 1982; CINTRÓN & SCHAEFFER-NOVELLI, 1983; SCHAEFFER-NOVELLI, 1995; CHEN and TWILLEY, 1998. KOCH and SNEDAKER, 1997.
INTERTIDAL ZONE (Constraint layer)	Red mangrove must be restricted to the intertidal zone	CHAPMAN, 1976; POOL et al., 1977; RABINOWITZ, 1978; SOTO and JIMÉNEZ, 1982; TOMLINSON, 1986; SCHAEFFER-NOVELLI, 1995; SOARES, 1999; MOSCATELLI, 2003.

Sediment type

Red mangroves are able to grow under variable soil composition, but Carmo et al. (1998) concluded that *R. mangle* is better adapted to fine sediments, such as predominate in sandy-clayey soils, especially those with higher concentrations of clay.

In Cardoso Island (Ilha do Cardoso), São Paulo, healthy stands of red mangrove can be found in places where the soil type is composed predominately by silt and clay particles. These sites also had the best conditions for underground plant development increasing the biomass (LOURO et al., 1994; CINTRÓN and SCHAEFFER-NOVELLI, 1983). As such, for this research, for areas to be considered as suitable sites for *R. mangle* the suitability criterion 'particle size' used was set to < 125 µm which includes the classification types for 'clay' to 'very fine sand'.

Organic matter content

Low organic matter content decreases the plant's health and leaves, making the species more susceptible to diseases (LARCHER, 2000). Usually, red mangrove stands grow in soils with higher organic matter content than other mangrove species (CARMO, 1998; TWILLEY et al., 1995; LOURO et al., 1994; CINTRÓN and SCHAEFFER-NOVELLI, 1983).

However, degraded areas often present lower soil organic matter content than a natural ecosystem. They would hardly be able to replace losses of organic matter (BROWN and LUGO, 1994) and often possess less organic matter than natural ecosystem areas. In this sense, the criterion 'organic matter content' cut-off level was set to >100 g/kg. This would allow areas with relatively low organic matter content to be considered for mangrove planting.

Interstitial water salinity

The influence of the interstitial water salinity in physiological processes in mangroves has been discussed by Soto and Jiménez (1982) and many other studies. The consequence of increasing salinity and its stress on plants is the inhibition of root growth and dwarfism (LARCHER, 2000). Cintrón and Schaeffer-Novelli (1983) have shown that high salinity levels can limit biomass accumulation, with significant reduction over 55 PSU. Lugo and Snedaker (1974) found best development conditions for mangrove forests in the Caribbean and the Gulf of Mexico where salinity is close to seawater's, i.e. about 35 PSU. On Caribbean islands, negative effects on mangrove structure were found in areas where salinity exceeded 50 PSU. In Puerto Rico Cintrón et al. (1978) found a relation of increasing salinity gradient and decline of mangrove structure. The same results were reported by Costa Rica by Soto and Jiménez (1982).

According to Chen and Twilley (1998) *R. mangle* would be the species most sensitive to high salinity when compared to *Laguncularia* sp. and *Avicennia* sp. However, lower salinities can favour the establishment of species that would not tolerate saline stress (MOSCATELLI, 2003).

Intertidal zone

As usual for mangroves, Red mangroves are restricted to the intertidal zone (MOSCATELLI, 2003; SOARES, 1999; SCHAEFFER-NOVELLI, 1995; TOMLINSON, 1986; SOTO and JIMÉNEZ, 1982; RABINOWITZ, 1978; POOL et al., 1977; CHAPMAN, 1976), as in places outside the intertidal zone, difficulties exist in the dispersion of propagules (RABINOWITZ, 1978), and in surviving competition with terrestrial species (MOSCATELLI, 2003). The tidal influence is an important factor for *R. mangle*, because beyond facilitating dispersion of its propagules (RABINOWITZ, 1978), it enhances the mangrove forests with influx of nutrients and the maintenance of interstitial water salinity to tolerable levels (POOL et al., 1977).

Table 1 shows the environmental ranges in which usually the *R. mangle* established as references in order to find sites most suitable sites. These parameters classified the Boolean images, as suitable or unsuitable sites for planting. We are aware other factors are likely to influence seedling growth (cf. KRAUSS et al., 2008; CANNICCI et al., 2008), but we adopt a simplified (reductionistic) approach.

RESULTS AND DISCUSSION

The model structure is simple, using two constraint layers which incorporated a) the exclusion of areas already occupied by existing mangroves, and b) areas outside the intertidal zone (Fig 3). Moreover, three thematic layers were integrated; a) sediment type (Fig. 4), b) organic matter content (Fig. 5), and c) the interstitial water salinity (Fig. 6). The latter were weighted equally according to the equation:

Suitable sites for planting *R. mangle* = (Suitable sediment type * Suitable organic matter * Suitable salinity) * (Intertidal zone * No mangroves cover).

Figure 3. Aerial photograph of the Itaipu Lagoon and the delimitation of the intertidal zone in black, ca. 29 ha in surface.

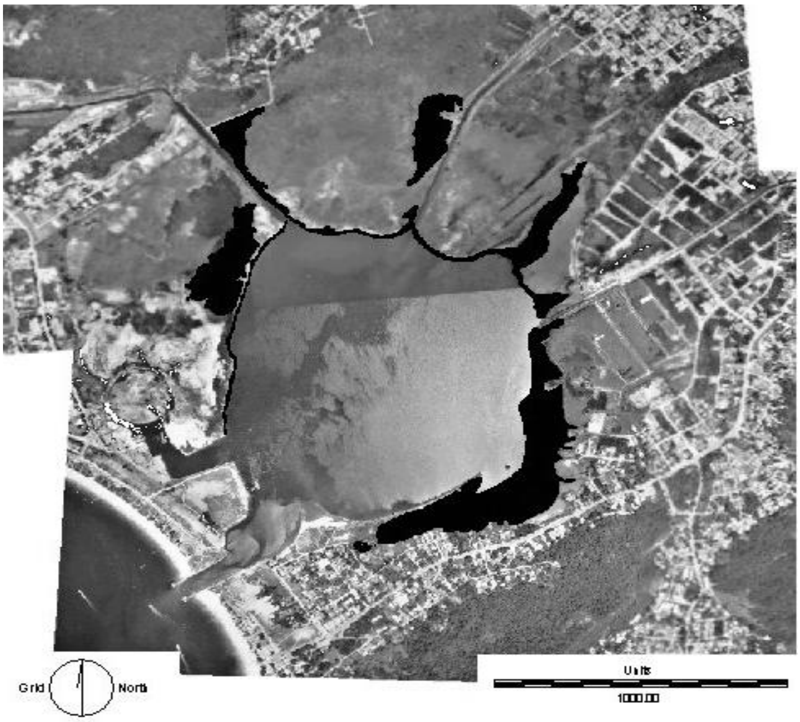


Figure 4. Spatial distribution of the sediment types (WENTWORTH, 1992) along Itaipu intertidal zone.

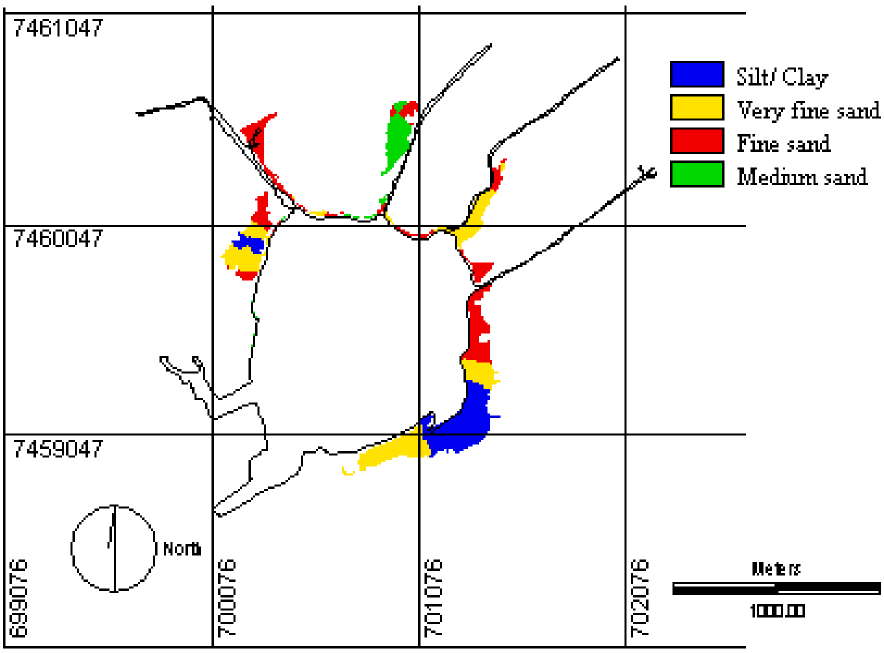


Figure 5. Spatial distribution of organic matter content (g/kg/10) along Itaipu intertidal zone.

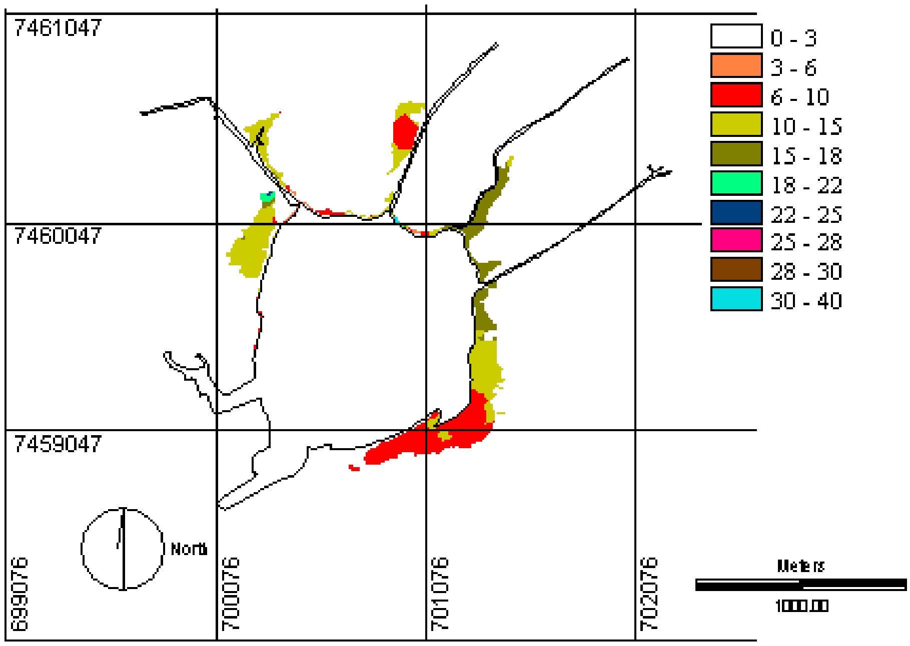
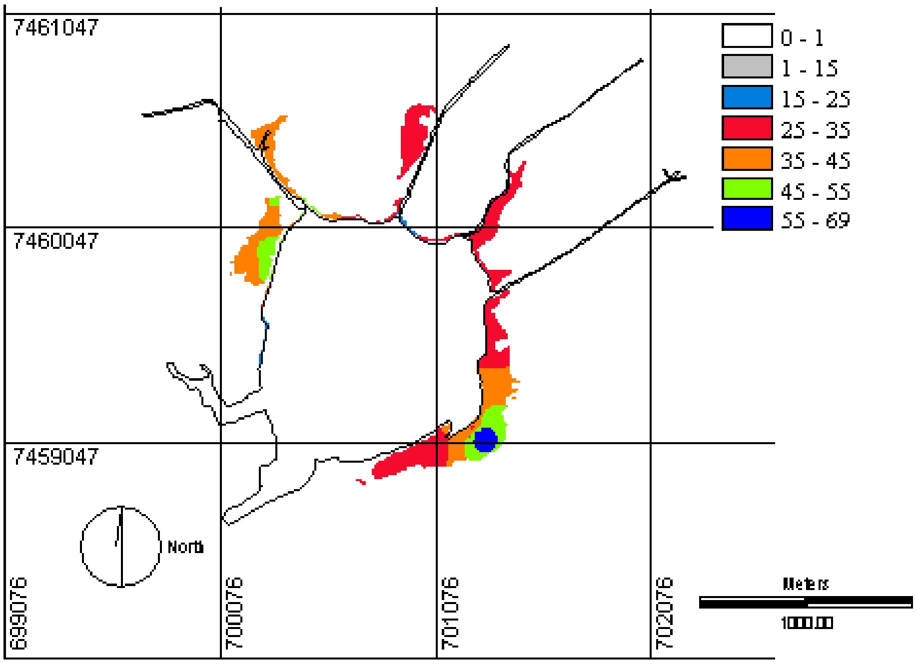
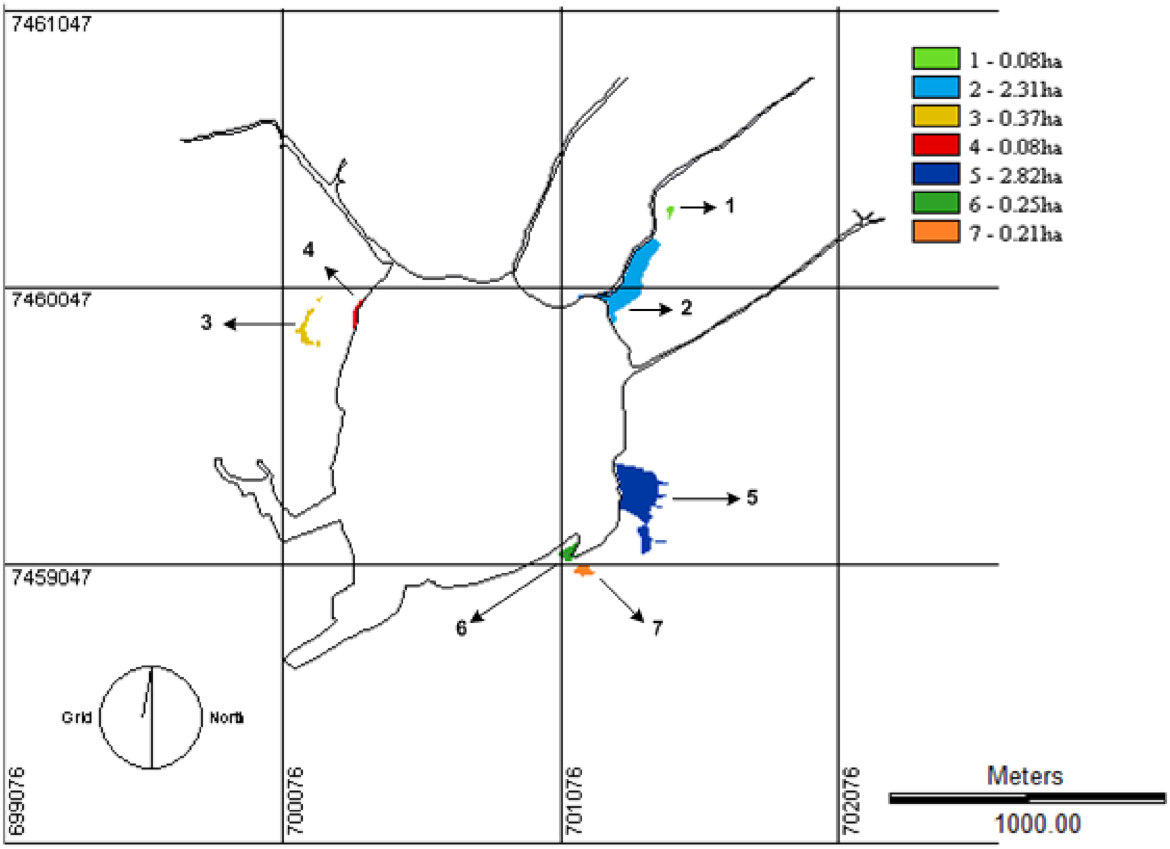


Figure 6. Spatial distribution of the interstitial water salinity (PSU) along Itaipu intertidal zone.



The resulting suitability map indicates seven suitable areas in the intertidal zone of Itaipu Lagoon (Fig. 7). These locations fulfil all the criteria set in table 1. The suitable patches were reclassified in three size classes, *ie*. small (<0.1 ha), medium (between 0.21 - 0.40ha) and large (> 2 ha) (Tab. 2). Small suitable areas < 0.08 ha were ignored. As concerns reforestation strategy, we would suggest that efforts be invested in the larger suitable areas, which are: Area 2 (2.3 ha) and Area 5 (2.8 ha) (Fig. 7).

Figure 7. Result of the Boolean overlay of the thematic layers. Seven suitable areas for *R. mangle* to be planted (21% of the total intertidal area) were identified. The numbers correspond to the areas described in table 2.



Area 1 was isolated by the larger sediment type (fine sand). Areas 3 and 4 presented narrow elongated shapes having this pattern because we excluded the area with vegetation. These forms can be explained by two factors: the pre-existence of a small mangrove forest and regions with fine sand. The two largest areas (Area 2 and 5) consisted mostly of very fine sand, salinity between 25-55 PSU and the presence of organic matter content between 100-180 g/kg.

The hydrodynamics of the Itaipu Lagoon works as a stream of seawater, which enters at the eastern side of the canal and flows towards the west in a counterclockwise sense once inside the lagoon. This explains the presence of a continuous region of silt / clay and very fine sand on the western side of the lagoon, resulting from lower energy in water flow depositing the smallest particles. In this way, the classification of suitable areas responded to changes in abiotic conditions determined by the hydrodynamics of the Itaipu Lagoon.

A community-based mangrove planting project pioneered by a local NGO (APREC) (FONSECA and DRUMMOND, 2003) and based on the intuitive experience of its members, has chosen another area for planting red mangrove propagules (i.e. the eastern side of the lagoon). This patch has been developed since 1999 to present.

This study has found a total of 6.12 hectares of suitable area spread over seven non-continuous patches. This represents roughly 21% of the total area analyzed. In this area, 15,300 red mangrove propagules could be planted using a grid spacing of 2m × 2m (Tab. 2).

Table 2. Suitable areas for planting the red mangrove species and the number of propagules (with the approximate costs already included).

Classes	Area (ID)	Size (ha)	Number of propagules needed (spacing 2×2m^2)	Planting cost (USD)
Large	5	2.82	7,050	5,929.91
(> 2 ha)	2	2.31	5,775	4,857.48
Medium	3	0.37	925	778.04
(0.20 – 0.4 ha)	6	0.25	625	525.70
	7	0.21	525	441.59
Small	1	0.08	200	168.22
(<0.1 ha)	4	0.08	200	168.22
Total	**7**	**6.12**	**15,300**	**12,869.16**

Using Moscatelli's estimated cost for mangrove planting in Rio de Janeiro, Brazil (USD 2,102.80/ha, pers. communication, 2004) under ideal conditions (absence of soil contaminants or solid residues, relative easy access throughout the terrain and ready availability of red mangrove propagules), it would take approximately 20 days with a party of 5 workers, plus a supervisor, to get the task done properly.

Here, we provided an estimate for how much it would cost to plant mangrove propagules in Itaipu Lagoon (Table 2). However, natural colonization by incoming floating propagules and the effort made by APREC and by the marine biologist Luiz Gonzaga, have restoration making progress at Itaipu Lagoon. If we would make a hypothetical estimation of cost for red mangrove planting in the whole area found suitable, it would sum up to USD 12,869. This estimate did not include the costing of this project’s field, lab and desk studies.

In a similar case, Thailand embarked on a mangrove rehabilitation program between 1996 and 2004 and found the cost per hectare to be from USD 8,812 to USD 9,318 (BARBIER, 2007). This restoration cost is higher than that costed by Moscatelli (ca. USD 2,100/ha), perhaps because of different socio-economic conditions between the two countries or due to different local environmental conditions. This study calculated the cost under ideal conditions as stated above.

Also, in Malaysia an estimated forest development and reforestation cost at average of USD 172.41 per ha for weeding and at between USD 470.22 and USD 626.96 per ha for replanting (ABDUL AZIZ et al., 2015).

Nevertheless, Barbier (2007) found that one hectare of mangrove generates an economic annual value of USD 12,392. In his evaluation, Barbier (2007) took in consideration other values from collected wood and non-wood forest products, fishery, nursery and coastal protection against storms.

In this sense, based on the study of Barbier (2007) the restoration in the two largest areas (2 and 5) that sum a total of 5.13ha could generate annually USD 63.570.

Figure 8. Two high-resolution images from IKONOS satellite available from Google Earth from 2003 (a) and 2012 (b). The arrows highlight the areas predicted to be suitable for regeneration and the areas where mangrove vegetation actually established. In green, the already existent mangrove vegetation; in blue, the correctly predicted suitable sites where mangroves have actually established; in orange, the site chosen by APREC for the reforestation; and in red, the sites we failed to predict as suitable but that were occupied by mangroves in 2012.

(a) (b)

Fonte: Google Earth.

The arrows in red show no vegetation cover in 2003 but nine years later mangroves are thriving in this area (Fig. 8). Our model did not predict these areas as suitable (Fig. 7 and 8a, b) because of the less appropriate soil texture at the time of fieldwork (fine sand in upper red arrow) or because of low organic matter content (i.e. <100 g/kg, lower red arrow) and in some parts by high interstitial water salinity (reaching values >55 PSU). Either *R. mangle* showed to be more tolerant than it was expected to be, and could therefore colonize more areas than predicted, or, more likely, this occurred in combination with changing environmental conditions over a period of 9 years that gradually made it possible for *R. mangle* to establish. Such strong dynamics with fast canopy turnover have been observed before along the North-Brazilian and French Guyana coast (FROMARD et al., 2004) and in Sri Lanka (SATYANARAYANA et al., 2013). Dahdouh-Guebas et al. (2005b) related such strong mangrove dynamics to human influences with respect to hydrography and hydrology. In our lagoon, coincidentally, we also observe that most mangroves have developed behind an artificial construction that probably accelerated the genesis of suitable areas and facilitated mangrove establishment.

The blue arrows show areas that corroborate the predicted results of the model. For instance, above area 5 (Fig. 7), mangrove did not grow and in our model, this same area was excluded due to unsuitable sediment type.

CONCLUSION

This approach is useful to integrate baseline environmental information on red mangrove requirements in a GIS environment, which can be used in finding areas where mangrove restoration will have the highest probability of success, the so-called map-based regeneration *sensu* Dahdouh-Guebas and Koedam (2002). Consequently, a down-to-earth approximate cost estimation can be made including the number of propagules and man-hours needed for mangrove restoration, that is if no other cheaper ways of rehabilitation are possible (*cf.* BOSIRE et al., 2008; STEVENSON et al. 1999; LEWIS and MARSHALL, 1997). Nonetheless, even if Brazil's economy has been changing since our 2004 estimation, our model provided a GIS-based method for selecting best target areas according to simple environmental variables for which values can be collected and integrated to provide a balanced first glance of cost/benefit of mangrove restoration project initiatives.

Hopefully this study will contribute to current reforestation projects using updated databases. Importantly, the methodology can with some adjustment of parameters, also be applied to other mangrove species in different regions. The selection of relatively small areas as suitable for planting of *R. mangle* emphasizes the importance of establishing parameters for resource optimization, because the stakeholders can redirect their efforts to larger suitable areas selected for restoration and leave the small areas to be naturally colonized. However, the lack of post-restoration monitoring in projects has limited the ability to evaluate which techniques produce better results (BOSIRE et al., 2008).

Therefore, future studies of long-term monitoring of the planted mangrove species need to be performed in order to investigate the use of GIS for decision support offered by this study. Although, in this research we used high-resolution images to verify new zones colonized by mangroves, these images did not provide information with respect to structural development and species composition.

Future studies on the current topic are therefore recommended to use a combination of other mangrove species, for instance, *Laguncularia racemosa* (L.) C.F. Gaertn and *Avicennia schaueriana* Stapf & Leech which are native mangrove trees from southeastern Brazil. Moreover, we suggest if possible, the inclusion of hydrodynamics and topographic variables as proposed by Di Nitto et al. (2014, 2013, 2008).

Future studies, should take in consideration a better distribution of sampling stations. With at least 30 or more sampling points randomly distributed over the whole area of interest and several station perpendicular to the topographic gradient.

This model was designed to select suitable areas where *R. mangle* will thrive, but it was also to choose the most suitable sites for where conditions will favour structural development. In this way, this study may contribute to carbon storage projects, because better developed forest structure provides a larger carbon sequestration potential.

The findings of this research suggest that planning restoration of mangroves using spatial analysis tools in GIS can be cost-effective especially if utilized over larger areas. Except for the suggestion of doing map-based regeneration by Dahdouh-Guebas and Koedam (2002), there has been little discussion on this topic on scientific literature, and the present study is to our knowledge the first to test it.

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