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Orientador: Eduardo Juan Soriano Sierra

Coorientador: Paulo Roberto Pagliosa Alves

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Restauração de manguezais no Brasil: retrospectiva e perspectivas
André Scarlate Rovai

Dissertação de Mestrado

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Programa de Pós-Graduação em Ecologia

UNIVERSIDADE FEDERAL DE SANTA CATARINA
DEPARTAMENTO DE ECOLOGIA E ZOOLOGIA

André Scarlate Rovai

RESTAURAÇÃO DE MANGUEZAIS NO BRASIL: RETROSPECTIVA E PERSPECTIVAS

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por

André Scarlate Rovai

Dissertação julgada e aprovada em sua forma final pelos membros titulares da Banca Examinadora (Port. 01/PPGECO/2012) do Programa de Pós-Graduação em Ecologia - UFSC, composta pelos Professores Doutores:

Banca Examinadora:

Prof. Dr. Eduardo Juan Soriano Sierra
(Presidente/ECZ/UFSC)

Profª. Drª. Yara Schaeffer Novelli
(Instituto Oceanográfico/USP)

Prof. Dr. Ricardo Palamar Menghini
(Instituto de Ciências da Saúde/UNIP)

Prof. Dr. Paulo Antunes Horta Junior
(Departamento de Botânica/UFSC)

Prof. Dr. Mauricio Mello Petrucio
Coordenador do Programa de Pós-Graduação em Ecologia

Florianópolis, 03 de fevereiro de 2012.

A minha esposa e meu filho, porque sem eles não experienciaria o mais puro amor.

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“O fracasso jamais o surpreenderá se sua vontade de vencer for suficientemente forte.”

(Enzo Scarlate, 2008)

RESUMO

Os objetivos deste trabalho foram realizar uma revisão dos trabalhos de restauração de manguezais realizados no Brasil, avaliando o estado da arte desta ciência no país e, testar experimentalmente se bosques de mangue restaurados por meio do plantio isolado de espécies vegetais típicas de mangue funcionam como bosques referencia. Para tanto, dados brutos de estudos independentes, obtidos através de sites de busca e material impresso, foram combinados em uma única análise. Os resultados mostraram que apesar de abrigar a terceira maior área de manguezal do mundo, o Brasil está em quinto lugar considerando o número de publicações indexadas sobre aspectos relacionados ao ecossistema manguezal, porém sem registros de trabalhos envolvendo restauração. Em contrapartida, a produção de literatura cinza vem crescendo durante a duas últimas décadas: 42 publicações compostas primariamente por trabalhos de conclusão de curso de graduação e de pós-graduação. Em relação aos resultados destes trabalhos, 40% dos experimentos de plantio conduzidos apresentaram taxas de sobrevivência variando de 0 a 20%, com o restante estando distribuído igualmente entre as demais classes de sobrevivência. Em termos de extensão de área, entre 1994 e 2010 foram plantados cerca de 2.617 ha, equivalente apenas a 5% de toda a área de manguezal já perdida no país. Sobre os aspectos metodológicos, os estudos examinados careceram de delineamento experimental adequado, comprometendo quaisquer conclusões consistentes acerca da dinâmica populacional e/ou de comunidades, assim como dificultando o processo de aprendizagem baseado em tentativas pretéritas. O segundo capítulo consistiu em um teste de hipótese, cujo objetivo foi avaliar se bosques de mangue plantados apresentam funcionalidade similar a bosque referencia. Para verificar possíveis similaridades foram caracterizadas a estrutura florestal e variáveis ambientais (granulometria, matéria orgânica, carbono, nitrogênio, fósforo, salinidade, elevação do terreno, freqüência de inundação e compactação do solo) de bosques de mangue plantados a cerca de 10-12 anos e de bosques referência (bosques em regeneração natural com idade similar aos plantados e bosques maduros). As características estruturais dos bosques plantados diferiram significativamente quando comparado aos referências. A análise de correlação múltipla indicou variáveis ambientais relacionadas a elevação do terreno (*pw*=0.521) como responsáveis pelos padrões de distribuição observados para a estrutura florestal. Resultados mostraram que mesmo decorridos 10-12 anos do plantio, seguido pela regeneração natural da vegetação, bosques replantados exibem padrões limitados de sucessão secudária, evidenciando que o plantio isolado pode ser ineficiente se as características da área objeto de recuperação, bem como da paisagem, forem desconsideradas. Assim, o manejo inapropriado de áreas sujeitas a restauração podem surtir conseqüências negativas sobre serviços ecossistêmicos tanto a curto quanto a longo prazo.

Palavras-chave: Restauração ecológica, meta-análise, plantio, implicações legais, reflorestamento, reabilitação, desenvolvimento estrutural, funcionalidade

ABSTRACT

In this work the goals were to review available national literature on mangrove restoration, performing a evaluation of the state-of-the-art of this science and, to experimentally test if stands restored by isolated planting of mangrove species function as reference sites. Raw data from independent studies, found and retrieved both through specific and ordinary search engines websites and printed material, was combined into a single comprehensive analysis. We found that besides accounting for the third largest mangrove area in the world Brazil holds the 5th position in mangrove publishing with no records on restoration. On the other hand, national gray literature production has shown an increase in the past two decades: 42 publications composed primarily by undergraduate and graduate thesis. Regarding outcome studies, 40% of the restoration experiments conducted had lower survival rates ranging from 0 to 20% with the remaining distributed evenly among other classes. In terms of area plantings conducted from 1994 to 2010 account for nearly 2,617 ha of restored area, equivalent only to ca. 5% of the area previously lost. Concerning methodological aspects, the studies examined lacked experimental design, compromising any consistent conclusions in light of population/community dynamics, as well as making learning from past experiences somewhat unattainable. In a second approach it was hypothesized that secondary succession on restoration sites that have been managed by single planting of mangrove species may be compromised by residual stressors, thus leveling off ecosystem's structural complexity and functioning at lower stages. To test this hypothesis forest structure and environmental characteristics of three replanted mangrove stands are compared with reference sites (natural regeneration stands of same age as replanted and natural old-growth forests). Structural attributes presented significant differences when comparing replanted and reference stands. Data sorted by height classes (cohorts) may be indicative of inferior regeneration potential in replanted stands. Multiple correlation analysis indicated variables related to elevation disruptions (*pw*=0.521) as the environmental drivers responsible for the patterns of distribution observed in forest structure. Results showed that after 10-12 years of planting followed by natural regeneration, restoration sites exhibited hindered patterns of secondary succession, evidencing that the isolated planting of single mangroves species can be ineffective if site and setting-specific characteristics are not considered. The inadequate management of restoration sites can, therefore, have implications on both immediate and long-term, large-scale ecosystem's services.

Keywords: Ecological restoration, meta-analysis, planting, policy implications, reforestation, rehabilitation, structural development, ecosystem functionality

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1 INTRODUÇÃO

Os manguezais cobrem cerca de 137.760 Km^2, distribuídos em 118 países e territórios, representando 0,7% de todas as formações florestais de todo o mundo (Giri et al. 2010).

Estas florestas provêem uma grande variedade de bens e serviços que beneficiam direta e indiretamente comunidades costeiras, incluindo produção de madeira para carvão e construção civil, produtos de efeitos medicinais, estabilização e proteção da linha de costa, proteção contra tempestades, manutenção da produtividade marinha e de habitats críticos para a reprodução e desenvolvimento de muitas espécies animais e vegetais (Walters et al. 2008). Recentemente, os manguezais foram ainda reconhecidos como componente chave no ciclo do carbono atmosférico, sendo considerados como as florestas mais ricas em carbono dos trópicos (Donato et al. 2011). Como consequencia, o valor monetário estimado pelos bens e serviços prestados pelos manguezais varia entre 200 e 900 mil dólares americanos por Km^2/ano (Wells et al. 2006).

A despeito de sua importância ecológica e econômica, os manguezais vêm desaparecendo em nível global a uma taxa de 0,7 (FAO 2007) a 2% (Lewis 2009b) por ano, principalmente em função da aquicultura, urbanização, poluição e alteração em zonas superiores das bacias onde se encontram (Duke et al. 2007). As perdas durante o último quarto de século variaram entre 35 e 86% a as taxas continuam aumentando principalmente em países em desenvolvimento, onde mais de 90% dos manguezais do mundo se localizam (Duke et al. 2007). Considerando a taxa atual de destruição, para estabilizar as perdas líquidas, seria necessário a efetiva restauração de no mínimo 150 mil hectares de manguezais degradados por ano (Lewis 2009b). Entretanto, a maior parte das tentativas de restauração de manguezais frequentemente fracassam devido as técnicas empregadas enfatizarem o plantio isolado de espécies vegetais típicas de mangue, desconsiderando por completo as razões pelas quais determinado manguezal foi degradado, bem como porque a regeneração natural não ocorreu (Erftemeijer & Lewis, 2000; Lewis, 1990a, 1999, 2000, 2005, 2009b).

No Brasil os manguezais são encontrados em proporções continentais, distribuídos entre as latitudes 04°30'N e 28°30'S, sujeitos a grande variedade de condições ambientais, apresentando diferentes arranjos espaciais de espécies (*Rhizophora mangle* L.; *R. harrisonii* Leechman; *R. racemosa* Meyer, Rhizophoraceae; *Avicennia schaueriana* Stapf & Leechman ex Moldenke; *A. germinans* L. Stearn, Acanthaceae; *Laguncularia racemosa* L. Gaertn. F., Combretaceae) e atributos estruturais (Rebelo-Mochel 1997; Schaeffer-Novelli et al. 1990, 2000). O Brasil detém a terceira maior área de manguezais do mundo, representando 7% de todos os bosques de mangue a nível global e 50% dentro da América Latina (FAO 2007; Giri et al. 2010). Não obstante, o Brasil perdeu 50 mil hectares de manguezais só nos últimos 25 anos, principalmente ao longo das costas sudeste-sul (FAO 2007) e as projeções sugerem que as taxas de perdas deverão continuar a aumentar rapidamente (Duke et al. 2007).

Assim como em outros países, esforços para a restauração de bosques de mangue foram engendrados, principalmente por meio de ações independentes objetivando compensar perdas locais, raramente excedendo poucas dezenas de metros quadrados. Ações mais expressivas, baseada nas lições apreendidas, são praticamente inexistentes.

Outras considerações inerentes à restauração deste ecossistema são as maneiras atualmente empregadas para se medir o sucesso das ações, majoritariamente baseadas no desenvolvimento estrutural das mudas plantadas. Mesmo que as mudas apresentem um bom desenvolvimento, períodos variando entre 10 e 50 anos podem ser necessários para se avaliar o sucesso de um plantio com base no desenvolvimento estrutural do bosque (Crewz & Lewis 1991; Lugo 1992; Luo et al. 2010). Ainda, considerando que o tempo necessário para se avaliar o restabelecimento da funções ecológicas pode ser maior do que o tempo requerido para o retorno dos atributos estruturais do bosques (Mckee & Faulkner 2000), resultados de curto prazo não devem ser considerados com restauração ecológica, mesmo que estes aparentem ser positivos (Ellison 2000; Lewis 2009).

Nesse sentido, os objetivos deste trabalho foram realizar uma revisão dos trabalhos de restauração de manguezais realizados no Brasil, avaliando o estado da arte desta ciência no país, e testar experimentalmente se bosques de mangue plantados funcionam como bosques referencia.

2 MANGROVE RESTORATION IN BRASIL: A CRITICAL REVIEW

2.1. ABSTRACT

In this paper we aimed to review the state-of-the-art science regarding mangrove restoration in Brazil, as well as explore where and why we went wrong and propose coarse corrections. Raw data from independent studies, found and retrieved both through specific and ordinary search engines websites and printed material, was combined into a single comprehensive analysis. We found that besides accounting for the third largest mangrove area in the world, Brazil holds the 5th position in mangrove publishing with no records on restoration. On the other hand, national gray literature production has shown an increase in the past two decades: 42 publications composed primarily by undergraduate and graduate thesis. Regarding outcome studies, 40% of the restoration experiments conducted had lower survival rates ranging from 0 to 20% with the remaining distributed evenly among other classes. In terms of area plantings conducted from 1994 to 2010 account for nearly 2,617 ha of restored area, equivalent only to ca. 5% of the area previously lost. Concerning methodological aspects, the studies examined lacked experimental design, compromising any consistent conclusions in light of population/community dynamics, as well as making learning from past experiences somewhat unattainable. In summarizing experiences accumulated to date and pointing out common and recurrent pitfalls, highlighting key references as well as proposing complementary steps in cases where mangrove planting is recommended, we hope to help break through the small scale gardening paradigm that still haunts restorationists' minds.

2.2. INTRODUCTION

Mangrove forests cover about 137,760 km^2 in 118 countries and territories, accounting for 0.7% of total tropical and sub-tropical forests of the world (Giri et al. 2010). These forests provide a wide variety of goods and services that benefit both directly and indirectly coastal communities, including wood for fuel and construction, medicines, coastal land stabilization and storm protection and the maintenance of critical nursery habitat and marine productivity which support coastal commercial fisheries (Walters et al. 2008). Moreover, mangroves have been recently recognized as a key component of the atmospheric carbon cycle, being the most carbon-rich forests in the tropics (Donato et al. 2011). Therefore, the monetary value of the products and services that mangroves provide have been estimated to be USD 200,000–900,000/Km^2/year (Wells et al. 2006).

Despite its ecological and economical importance, mangroves are disappearing worldwide by 0.7 (FAO 2007) to 2% (Lewis 2009b) per year, mainly due to aquaculture, urbanization, coastal landfill, pollution and upstream land use (Duke et al. 2007). Losses during the last quarter century ranged consistently between 35 and 86% and rates continue to rise more rapidly principally in developing countries, where > 90% of the world's mangroves are located (Duke et al. 2007). Considering the current destruction rate, to achieve no-net-loss of mangrove forests, a minimum of 150,000 hectares of successful mangrove forest restoration per year would therefore be required (Lewis 2009b). However, most attempts to restore mangroves often fail completely and evidence for successful restoration on any large scale is nearly non-existent (Lewis 1990a; 1999; Erftemeijer & Lewis 2000; Lewis 2000; 2005; 2009b).

In Brazil, mangroves are found in continental proportions, spread out from 04°30'N to 28°30'S latitudes, under a wide array of environmental conditions and with variable spatial arrangements of species (*Rhizophora mangle* L.; *R. harrisonii* Leechman; *R. racemosa* Meyer, Rhizophoraceae; *Avicennia schaueriana* Stapf & Leechman ex Moldenke; *A. germinans* L. Stearn, Acanthaceae; *Laguncularia racemosa* L. Gaertn. F., Combretaceae) and stand structural attributes (Rebelo-Mochel 1997; Schaeffer-Novelli et al. 1990; 2000). The country accounts for the third largest mangrove area in the world representing 7% of world's mangrove coverage and 50% of all South America's (FAO 2007; Giri et al. 2010). Nevertheless, Brazil has lost at least 50,000 ha of mangroves over the last 25 years, mainly along the southern coast (FAO, 2007) and projections are that rates will continue to rise more rapidly (Duke et al. 2007). These projections are very likely be expedited since a revision to the country's Forest Act (the main Brazilian environmental legislation on private land), proposing the conversion of up to 35% of all salt flats into shrimp ponds, has been submitted to Congress, and there is a strong chance that it will be approved (Calmon et al. 2011; Metzger et al. 2010; Nazareno 2012).

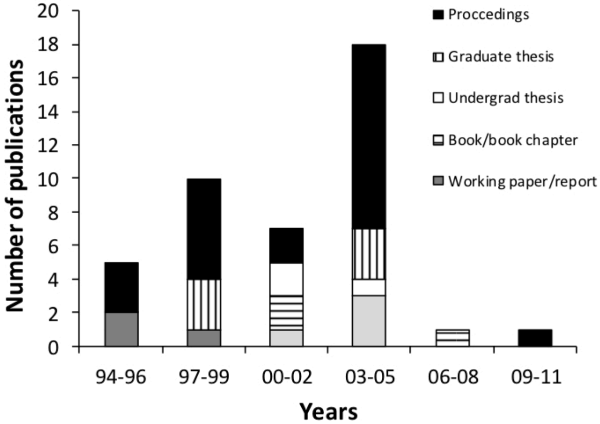
As in other countries, restoration efforts have been made in Brazil, but mainly through independent attempts aiming to compensate local (rarely exceeding tens of square meters) losses. Broader efforts, based on lessons learned and contextualizing what is known, are virtually inexistent. In this paper we intended to combine results from different studies on mangrove restoration that have been carried out in Brazil in order to draw general conclusions. First, we performed a systematic review aiming to find any available literature on mangrove restoration. Then, we examined raw data from all studies and selected the ones where common statistical metrics could be obtained and combined these into a single analysis. Finally, based on qualitative and quantitative data, we considered how to scale up ongoing from practices that have been employed towards larger scale restoration of tidal forests, proposing ways to move from small scale gardening to effective ecological mangrove restoration.

2.3. RE-INVENTING THE WHEEL

Methods for planting mangroves are well known and well developed and although these methods have remained virtually unchanged they are continually rediscovered in field trials conducted worldwide (Ellison 2000). While scientists abroad have been testing for the last four decades a wide array of mangrove restoration methodologies, from aerial propagule planting (Teas & Jurgens 1978) to ecological engineering (Lewis 2005), with many unsuccessful cases related to planting and redundant planting in non-suitable sites being reported (Banner 1977; Erftemeijer & Lewis 2000; Hamilton & Snedaker 1984; Hannan 1975; Kinch 1975; Lewis 1990; 1999; 2000; 2005; 2009b; Samson & Rollon 2008; Teas et al. 1975; Teas & Jurgens 1978b), we here seem to have reached a learning plateau, stuck in a "re-inventing the wheel" sort of process.

From 1959 to 2011, 7,853 mangrove articles were published out of which 200 (1994-2011) were about restoration (ISI's Science Citation Index). Brazil holds the fifth position, with 7% (n=554) of the scientific production distributed among the Web of Science categories, but with no records regarding restoration. On the other hand, the national gray literature production on mangrove restoration has shown an increase in the past two decades (Fig. 1), with the experience narrowed to 42 publications, all restricted to planting techniques (Table 1).

Figure 1 – National production (gray literature) on mangroves. Searches were performed at Web of Knowledge, Scopus, Scielo and Capes thesis data-base using as keywords “mangrove”, “restoration”, “recuperation”, “rehabilitation”, “forestation”, “aforestation”, “reforestation”, “planting”, “replanting”, always associated with the word “Brazil”. We performed as well searches at ordinary searching sites aiming to find unpublished documents that could have been made available on-line to consultation. Searches were made in English and Portuguese languages.



Most of the work conducted in Brazil has been part of undergraduate and graduate theses, which are then rewritten into short papers (Table 1) often published more than once as proceedings articles: we found that 60% of the studies that presented sufficient statistical information (number of experiments within each study ≥2) are based, in fact, on the same dataset.

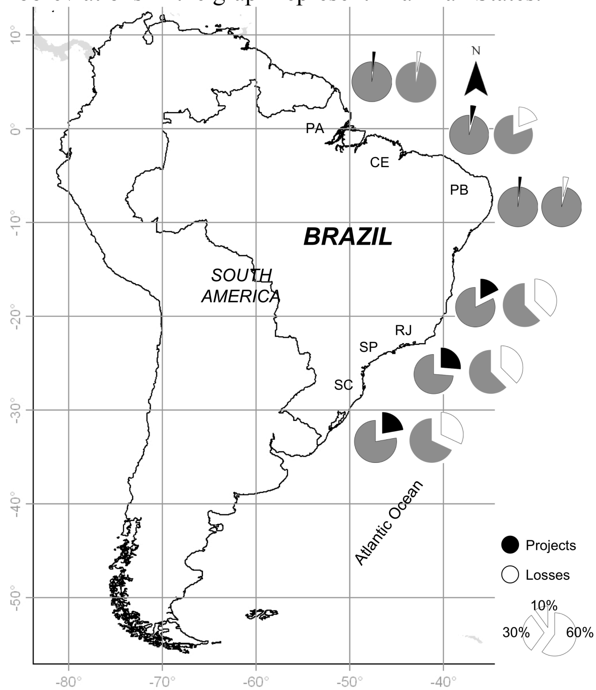
Regarding the geography of mangrove planting efforts the larger plantings are found in the north-northeast region (MMA 2010), whereas most activities took place along south and southeast coast (Fig. 2), also where higher losses were recorded (FAO 2007), probably reflecting the greater and faster urban and industrial expansions, as well as increasing harboring activities observed in this region.

Table 1 - Methodological details of mangrove planting studies conducted in Brazil. (*) Study not found; (**) data obtained (cited) from another study and (***) adopted planting spacing (when not provided) to allow area estimation. Rm - *R. mangle*; Lr - *L. racemosa*; As - *A. schaueriana*; Ag - *A. germinans*. Full references (gray literature) provided as supplementary material.

Project goal	Location (Lat/Lon; State)		Number of propagules/ seedlings	spp used	Planting spacing (m x m)	Restoration area (ha)	Publication type	References (data set)
Mangrove re-establishment	22°56'S/43°08'W	RJ		Rm			Proceedings	Moscatelli & Almeida (1994)**
Mangrove re-establishment	22°56'S/43°08'W	RJ		Rm	0,5 x 2,0		Proceedings	Moscatelli et al. (1994)
	22°56'S/43°08'W	RJ					Proceedings	Moscatelli et al. (1997)*
Mangrove growth performance	12°59'S/38°36'W	BA	1190	Rm	0,5 x 0,5	0,029	Masters thesis	Orge (1997)
Mangrove planting experimentation	24°00'S/46°35'W	SP	1592	Rm	1,5 x 1,5***	0,358	Proceedings	Eysink et al. (1997, 1998a)
Mangrove planting experimentation	24°00'S/46°35'W	SP	187	Lr	1,5 x 1,5***	0,042	Proceedings	Eysink et al. (1998b)
Mangrove re-establishment	27°26'S/48°28'W	SC	120	Rm, Lr, As	1,0 x 1,0	0,012	Masters thesis; Proceedings	Abrahão (1998); Abrahão et al. (1998)
Mangrove re-establishment	07°02'S/34°52'W	PB	4167	Rm, Lr, As	1,5 x 1,5	0,937	Book	Paludo & Klonowski (1999)
Mangrove re-establishment	24°00'S/46°35'W	SP	572	Rm, Lr	0,5 x 1,0	0,028	PhD thesis; working reports (3); proceedings (2); journal	Menezes (1999); Menezes et al. (1994, 1995, 1996, 1997, 1998, 2005)
Mangrove re-establishment	27°26'S/48°28'W	SC	1000	Rm, Lr, As	1,5 x 1,5***	0,225	Book; proceeding; masters thesis	Cunha (2000b); Cunha et al. (2003); Huber (2004)
Mangrove re-establishment	27°26'S/48°28'W	SC	137	Rm, Lr, As	1,5 x 1,5***	0,030	Book; masters thesis	Cunha (2000c); Huber (2004)
Mangrove re-establishment	24°00'S/46°35'W	SP		Rm, Lr			Proceedings	Castanheira et al. (2001)**
Mangrove re-establishment	27°26'S/48°28'W	SC	225	As	0,7 x 0,7	0,011	Undergraduate thesis; proceedings; masters thesis	Cunha (2000a); Cunha & Panitz (2001); Huber (2004)
Mangrove re-establishment	27°26'S/48°28'W	SC	965	Rm, As	1,0 x 1,0	0,108	Undergraduate thesis	Matos (2002)
Mangrove re-establishment	22°56'S/43°08'W	RJ		Rm, Lr, As	1,4 x 1,4		Proceedings (2)	Louzada et al. (2003a, 2003b)
Mangrove re-establishment	22°56'S/43°08'W	RJ		Rm, Lr, As	1,4 x 1,4		Proceedings (2)	Louzada (2003); Louzada et al. (2003c)
Mangrove growth performance	22°56'S/43°08'W	RJ	330	As		0,074	Proceedings	Pereira et al. (2003)
Mangrove re-establishment	03°45'S/38°31'W	CE		Rm, Lr, As			Proceedings	Bonilla et al. (2003)
	25°30'S/48°19'W	PR					Proceedings	Sessegolo et al. (2003)*
Mangrove re-establishment	27°26'S/48°28'W	SC	350	Lr	1,5 x 1,5***	0,078	Journal (3)	Tognella-de-Rosa et al. (2002, 2003, 2004)
		SC					Undergraduate thesis	Neto (2004)*
Mangrove re-establishment	24°00'S/46°35'W	SP	1890	Rm, Lr, As	1,2 x 1,2	0,272	PhD thesis; proceedings (2)	Castanheira (2004); Castanheira et al. (2005a, 2005b)
Mangrove growth performance	24°00'S/46°35'W	SP	750	Rm	0,5 x 1,0	0,037	PhD thesis	FrueHauf (2005)
Mangrove re-establishment	22°56'S/43°08'W	RJ		Rm, Lr, As			Proceedings	Louzada et al. (2005)
Mangrove re-establishment	00°33'S/47°44'W	PA	470	Rm, Ag	1,0 x 1,0	0,047	Book chapter	Fernandes et al. (2007)
Mangrove re-establishment	03°45'S/38°31'W	CE	360	Rm	3 x 3	0,324	Proceedings	Bonilla et al. (2010)
TOTALS			**14.305**			**2,617**		

Considering the losses during this last quarter of century (FAO 2007), if mangrove forest destruction remains at the same pace, a no-net-loss of mangrove areas we would require effective restoration of 2,000 ha/year and about double that amount to bring back what has already been lost. Nevertheless, assuming a conservative point of view, where all restoration efforts (resumed to planting of single mangrove species) summarized in this work had a one hundred percent success rate, we would have "restored" from 1994 to 2010 nearly 2,617 ha (Table 1), equivalent only to ca. 5% of the area already lost.

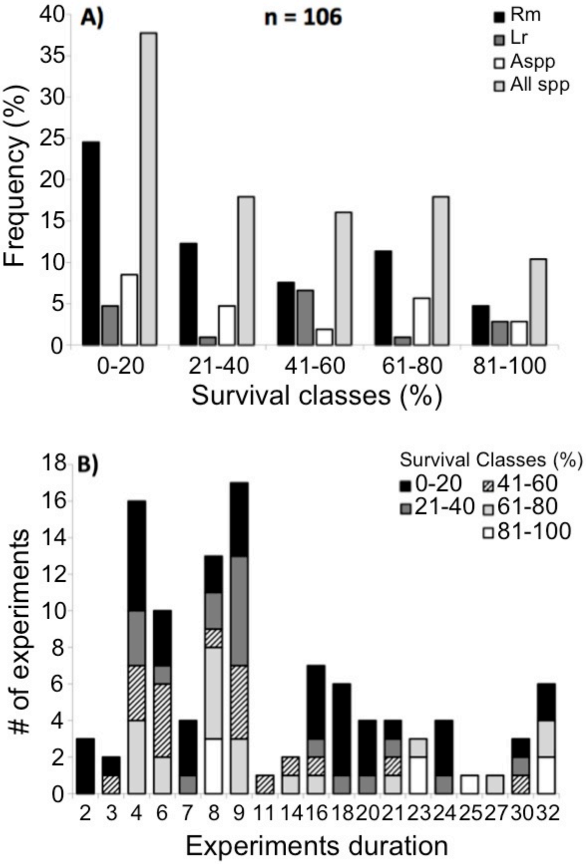
Figure 2 – Geography of mangrove restoration in Brazil. Conversely to area extension, most restoration efforts occurred mainly along south-southeast coast, also where larger areas of mangrove were lost (percentage values). Sources for area loss: Silva et al. (1991); Kjerfve & Lacerda (1993); Sierra de Ledo & Soriano-Sierra (1998); Cohen & Lara (2003); Lacerda et al. (2006); Pires (2010); Bernini et al. (2010) and for number of publications: same of table 1. Full references (gray literature) provided as supplementary material. Abbreviations in the graph represent Brazilian States.



A general overview on the survival outcomes reveal that almost 40% of the experimental plantings conducted had lower survival rates ranging from 0 to 20% and the remaining was evenly distributed among other survival rates, regardless the species used (Fig. 3 A). Taking species into consideration, *Rhizophora mangle* produced the best survival outcomes, but this could be due to the number of experiments made with this species (n=64) having outnumbered experiments using *Laguncularia racemosa* (n=17) and *Avicennia* spp. (n=25) by at least 2.5 and 3.8 fold, respectively.

Coupling survival outcomes with duration provides a more solid interpretation (Fig. 3 B). Those experiments that are of short duration and higher survival rates should not be interpreted as successful cases; rather they make it impossible to draw any consistent conclusions about survivorship. Furthermore, some studies that were concluded within the first 6 months (Abrahão 1998; Matos 2002) performed experiments using protected (encasement made with PET soft drinks bottles) and non-protected treatments, which certainly leads to biased results; at the end of each study, survivorship was bearing zero in non-protected treatments while much higher on the other ones. Question is: what would be the following month scenario after the last record was made and protection removed? Our guess is that bars on the left side of Fig. 3A would get higher. In fact, a recent survey on one of the areas (planting executed by Matos 2002) revealed that the massive planting of 720 *A. schaueriana* propagules was in vain, since *L. racemosa* is the dominant species with virtually absent *A. schaueriana* individuals (Rovai et al. 2011).

Figure 3 – Percentage of experiments distributed in survival classes (A) and survival classes at experiments end-points (total monitoring time) (B). To assure data independence only final survival rates were computed. In A, because of the reduced number of studies using either *A. schaueriana* or *A. germinans* we treated these species together referring to them as Aspp in the present and following analysis. Rm=*R mangle*; Lr=*Laguncularia racemosa*.



2.4. WHERE WE WENT WRONG

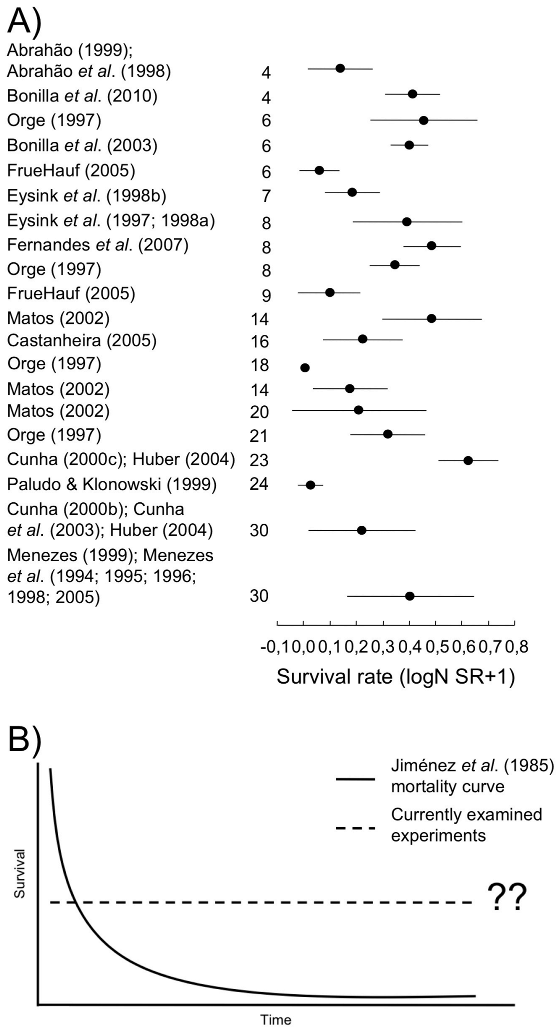
Duration of experimental observation is an important consideration on survival experiments, and without long-term research observations studies results can became irrelevant. Some articles published in meeting proceedings were based on only 2 months of field observation (Table 2). Undergraduate and masters thesis relied on field data collected over 4 to 21 months periods while PhD's researches dedicated between 16 to 32 months to field work. However, even 32 months field monitoring can be considered an insignificant amount of time if the research goal is ecosystem restoration or even if the goal is to assess forest structure recovery, given the dynamics inherent to successional processes as well as time required for stand to mature. Periods ranging from 10 through 25 (Crewz & Lewis 1991) to 50 years (Lugo 1992; Luo et al. 2010) may be required to evaluate mangrove restoration success based on vegetative structural characteristics. Additionally, the time lag required to assess ecosystem functionality is longer than the time lag needed to assess survival of the vegetation and the overall structural attributes (Mckee & Faulkner 2000). After 10 or more years, restored stands can present different trends in forest structure when compared to same age reference sites (Rovai et al. 2011), and in some cases even 3 decade old restored stands can disappear completely (Hamilton & Snedaker 1984).

Another aspect of the cases examined is the absence of experimental design (*sensu* Underwood 1994; 1997) and/or criteria used to determine if a site would or would not be suitable for restoration. Some studies mentioned that the choice for the restoration site was based on the presence or absence of volunteer plants, as if they were indicators of natural recovery, or on the fact that the site used to be a mangrove before the impact. However, such a assumption should take into consideration local environmental drivers in mangrove establishment and early development (Krauss et al. 2008) and thresholds to mangrove seedling establishment (Balke et al. 2011), therefore predicting if a given site is suitable or not to be restored by plant enrichment.

Some mangrove propagules have large nutrients storages, particularly *R. mangle*, which was the species most largely used in the studies examined. This storage allows survival even if environmental conditions are adverse during early development, giving the false impression that natural regeneration is taking place. Temporary patches of volunteer mangroves can be seen even in high energy environments, such as in beaches sand bars and along river banks, usually during benign conditions or where protected by larger and heavy obstacles (rocks, dead tree trunks), but that does not mean natural regeneration has or will take place. A slight shift in the environmental conditions is what it takes to sweep always those volunteers. Also, choosing a reference site based on the fact that the area used to be a mangrove can lead to methodological mistakes. For example, the physical environment could have been drastically altered (by erosion, topographic level, hydrology, sediments chemical composition) and the site may no longer be suitable to sustain mangrove communities. Additionaly, mangrove stands are nested in sub-settings, which in turn constitutes a module of the landscape. Thus, stands are necessarily subjected to oscillations on higher levels of organization and the success of isolated approaches will invariably depend on the environmental conditions of the levels above (Lugo 1978; Schaeffer-Novelli et al. 2005).

Long-term approaches and experimental ecology design (appropriate replication and the use of reference sites for comparisons) omissions make it impossible to draw any conclusions in light of population/community dynamics (mortality as a function of time). Yet, a comparison made between the investigated studies revealed no pattern regarding survival as a function of time; conversely it showed variability even when same or close end-points studies were compared (Fig. 4 A). Contrarily, in "natural" conditions (as it would be expected for a reference site, in a experimental design context) mortality can be described as a function of time (Jiménez et al. 1985) hence allowing predicting trends in population/community homeostasis (Fig. 4 B).

Figure 4 – Combination of the investigated studies results (A) and analogy between Jiménez et al. (1985) mortality curve (adapted) for natural stands and trend observed based on the investigated studies (B). To compare studies survival outcomes we calculated a index (SR - Survival Rates) for each experiment (individual planting plot/area) within each study based on final(f) and initial(i) absolute survival values $(SR = \ln(\bar{X}_f/\bar{X}_i) = \ln(\bar{X}_f) - \ln(\bar{X}_i))$. The natural log was used because it linearizes the metric, treating deviations in the numerator the same as deviations on the denominator, and also because it provide a much more normal distribution of SR values. Individual SR's were then computed into mean SR values for each study. Mean SR were computed from final survival rates that had the same or approximately the same (±1 month) monitoring time. Thus, experiments within the same study but with different (>1 month) monitoring times between them were either grouped (considered as if they were independent studies, when n≥2) or excluded from the analysis (when n=1). Confidence intervals $(95\%CI = SR \pm 1.96 \times SE)$, were then calculated.



2.5 WHY WE WENT WRONG

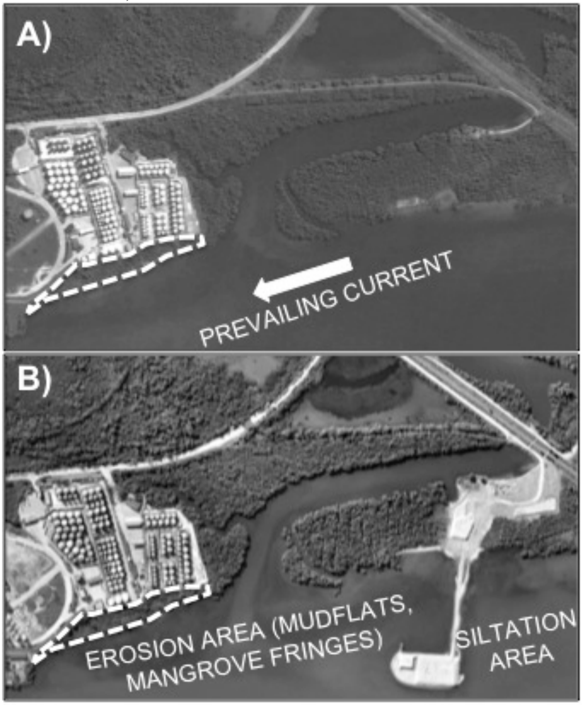
We believe that such a delay in the mangrove restoration records for Brazil relies on four interconnected main causes. First, interests on mangrove research in Brazil only arose in the late 1970's, with most efforts focused on basic descriptive ecological studies (Schaeffer-Novelli & Cintrón 1990). As a consequence of not having mangrove studies institutionalized, Brazil now faces a gap in terms of effective policies regarding mangrove ecosystems restoration, which we consider the second cause of the problem.

Brazil does not have a federal code that establishes steps to be taken in order to restore a degraded mangrove area; the only regulatory, state-based norm (SMA 2008), is superficial and places all Atlantic Rainforest vegetation formations in the same category, regulating only the kinds of species to be reintroduced without taking into account the complexity of the ecosystem as a whole (i.e., interactions, functionality). In addition, since restoration methods in Brazil were developed for rainforests and seasonal forests, it is hard to state if and how these methods are relevant to other systems such as mangrove forests (Rodrigues et al. 2009). Another problem regarding fixed rules is that nature cannot be managed by rigid recipes. By doing so, professional's creativity and skills are limited to a narrow range of possibilities (Durigan et al. 2010) – in Brazil's case, restricted to planting.

The dearth of science-based policy instruments leaves a gap that has to be filled by the actors involved in the case. This leads us to the third breach: lack of qualified personal designing and analyzing restoration projects. The absence of reliable guidelines means stakeholders are forced to make decisions relying upon poor and inappropriate information. It is estimated that only 20% of the master's in ecology that graduated in the 90's are currently working outside the academia, indicating a huge gap in both public and private sectors due to the lack of qualified staff (Scarano & Oliveira 2005). Those working in environmental protection agencies are usually overloaded with daily demands, making it harder for them to acquire practical, field based decision-making knowledge. This way, the assessment of restoration projects ends up becoming mere desktop bureaucratic formality (Box 1 brings a case experienced by some of this paper's authors that well illustrates the situation abovementioned).

Box 1 - Under the aegis of the Local Environmental Protection Agency (DEPRN/CETESB) a mangrove restoration project became a rigid complete failure due to the agency's instructions to restore a site damaged by fire and chemical spill (Menghini et al. 2011). Even after being alerted that neither the methodology (REM by Riley & Kent 1999), nor the site was suitable for restoration, The agency's decision prevailed. Results were as expected: after nearly a decade of planting and redundant replanting of Rhizophora mangle propagules (n=477, without considering replantings) inside PVC tubes, only 1.26% of survival was registered (Coelho-Jr 2007, unpublished report). To make matters worse, a private owned harbor facility was approved by environmental authorities and is currently being installed in a neighboring area. The restoration area is now likely to disappear completely due to increased erosion (Fig. 5).

Figure 5 – Case study at Barnabé Island, Santos estuary (southeastern Brazil). Prior (A; situation until 2008) and after (B; situation in 2009) harbor facility installation. Dotted line indicates the restoration site described and manipulated by Coelho-Jr (2007, unpublished report). In B it is possible to foresee the fate of the area supposed to be restored, as erosion is expected to sweep the narrow mangrove fringe away. Images from googleeartth.com (image A from 2003 and B from 2009).



The majority of environmental professionals engaged in restoration are not well prepared. The bulk of science graduates, mainly those emerging from courses rooted in the hard sciences (forestry engineering, environmental engineering, agronomic engineering, environmental sciences, etc.), move from the classroom directly to the working market, lacking professional and scientific experience. Once professional life begins it becomes difficult for most to engage in research and long-term field experiments related to effective ecological restoration.

Fourth and last, the lack of access and systematic archiving of data within the environmental agencies makes it difficult to find mangrove restoration files among thousands of other existing ones. This is a problem that seems to be persistent and world spread considering the difficulty in obtaining access to the international agencies, consultants and sponsoring agencies archives, making it impossible to carry out a critical review (Field 1999). Also, few scientists or organizations wish to report or document unsuccessful (or only partially successful) projects (Lewis 2005). Either way, it turns out that many mangrove restoration programs are being carried out without any reference to lessons that might be learnt from past experiences (Field 1999; Ellison 2000; Lewis 2005; 2009a; 2009b).

2.6. GETTING IT RIGHT: THOUGHTS FOR FUTURE ACTIONS

Among several types of wetlands, from estuarine, coastal and freshwater marshes, freshwater forests, groundwater seepage slope wetlands to seagrass meadows, mangrove forests are shown as one of those types that ought to be successfully restored most of the time (Lewis 2011) and over the past three decades many scientists have stated that the best way to do so is by eliminating the stressor and, when needed, assisting natural recovery (Cintrón & Schaeffer-Novelli 1983; Field 1999; Lewis 1982; 2005; 2009; 2011), by restoring natural subsidies (such as hidrology). Current practices keep us at the bottom of the restoration learning curve (King 1991), as we remain re-discovering, experimenting and implementing the same methods on poorly designed small-scale projects.

We propose four main reasons to why mangrove restoration science has not evolved in Brazil and we believe that the way to move up the curve is the increased involvement of capable personal in project designing and execution, chiefly on those cases where environmental impacts are foreseeable and mitigation will be required (i.e., environmental permitting/regulatory processes).

We also would like to call attention to the methods used to evaluate restoration outcomes (Lewis 2011): for those who claim restoration success based on seedling or tree development (i.e., production of leaves, growth rates, etc.) it is important to highlight that emphasis on planting a single mangrove species is not ecological restoration, even if it works (Lewis 2009b), therefore it should not be considered a “successful” restoration effort (Ellison 2000).

Regarding the absence of norms, we believe that hand/guidebooks could be very helpful, but caution must be draw to avoid generalization, especially in a country like Brazil that presents a great latitudinal gradient along its almost 5.000 miles of coastline. Such guides should focus on hydrological and topographical restoration, taking into consideration local and regional factors, rather than on the reintroduction of one or another ecosystem's component.

2.7 CLOSING REMARKS

Mangroves have been recently recognized as a key component of the atmospheric carbon cycle, being the most carbon-rich forests in the tropics (Donato et al. 2011). Yet together with marshes and seagrasses mangroves cover only less than 0.5% of the sea bed, alone they account for more than 50% of the earth's blue carbon sinks and for 71% of all carbon storage in ocean sediments, which can remain stored not for decades or centuries (like for example rainforests), but rather for millennia (Nellemann et al. 2009).

Due to its dynamic nature, mangroves rarely conform to classical concepts of forest development and functioning. Contrary to terrestrial vegetation, old-growth mangrove forests are, in fact, net producers of carbon, presenting higher gross primary production/respiration ratios than younger and more disturbed stands (Alongi 2011). Thus, the replacement of such established systems translates into loss of unknown information, therefore restoration becomes an unattainable intent and the use of such terminology should be pondered. However, rehabilitation is possible by re-setting environmental drivers that will allow analogous systems to develop under prevailing conditions. Hence, effective mangrove rehabilitation is a potential tool for mitigation of CO^2 emissions and offers long terms benefits in greenhouse gases concentrations as well as in the provision of immediate ecological services.

Lastly, acknowledged independent ecological mangrove restoration literature implies a common, universal message: that we all should learn from our past experiences, especially with the mistakes made. In summarizing experiences accumulated, pointing out common and recurrent pitfalls, highlighting key references as well as proposing complementary steps in cases where mangrove planting is inevitable (or highly desirable), we hope to help break through the small scale gardening paradigm that still haunts restorationists minds.

Box 2 - Implications for practice

- When mangrove planting is required (i.e., propagule limitation) or desirable (experimental designs, research) conduct a pilot-study consisting of monitoring natural recovery and assessing environmental factors related to hydrology and edaphic conditions; both within restoration site and in nearby areas to verify which species present greatest tolerance to the conditions in which they develop (environmental drivers). This information could be valuable for appropriate species selection.
- Examine climate records for low frequency but consequenting events (droughts, storms). Use local knowledge to complement hard data and weather records.
- Properly address spatial and temporal replication, and include reference sites nearby and within restoration site (to assess natural recovery within restoration site). This allows more robust statistical inference and results can be more acceptably extrapolated.
- Punctual short-term (undergrad, masters or even PhD research) should not be totally discontinued after authors have completed their academic requirements. Supervisors may play an indispensable role on the continuity of a once commenced research, reinforcing internal lab priorities for new candidates. Consider establishment of long-term research plots.
- We believe that after following these ideas, one might be able to achieve what is our last appeal (and everybody's desire): to publish your findings, being them successful or not. This is the only way we can have access to previous experiences, thus learning from them and advancing in the field.

3 MID-TERM ASSESSMENT OF REPLANTED AND NATURAL MANGROVES: WHAT SECONDARY SUCCESSION CAN TELL US ABOUT THE FATE OF FOREST STRUCTURAL COMPLEXITY AND FUNCTIONING

3.1 ABSTRACT

Under ideal conditions mangrove forests unfold into their high-end manifestation, therefore functioning at full throttle and delivering ecosystem's services at their best. In this work we hypothesized that secondary succession on restoration sites that have been managed by single planting of mangrove species may be compromised by residual stressors, thus leveling off ecosystem's structural complexity and functioning at lower stages. To test our hypothesis forest structure and environmental characteristics of three replanted mangrove stands are compared with reference sites (natural regeneration stands of same age as replanted and natural old-growth forests). Structural attributes presented significant differences when comparing replanted and reference stands. Data sorted by height classes (cohorts) may be indicative of inferior regeneration potential in replanted stands. Multiple correlation analysis indicated variables related to elevation disruptions (*pw*=0.521) as the environmental drivers responsible for the patterns of distribution observed in forest structure. Results showed that after 10-12 years of planting followed by natural regeneration, restoration sites exhibited hindered patterns of secondary succession, evidencing that the isolated planting of single mangroves species can be ineffective if site and setting-specific characteristics are not considered. The inadequate management of restoration sites can, therefore, have implications on both immediate and long-term, large-scale ecosystem's services.

3.2. INTRODUCTION

Mangrove ecosystems provide a wide spectrum of goods and services that benefit societies both directly and indirectly, including wood for fuel and construction, medicines, coastal stabilization, storm protection and productivity that sustains critical nursery habitat and coastal commercial fisheries (Walters et al. 2008). Moreover, these forests have been recently recognized as a key component of the atmospheric carbon cycle, being the most carbon-rich woodlands in the tropics; playing a major role in climate stabilization (Alongi 2011; Donato et al. 2011; Nellemann et al. 2009). Monetary value of the products and services that mangroves provide has been estimated to be

USD 200.000–900.000/Km^2/year (Wells et al. 2006), not including the recently recognized role in climate regulation.

Despite their undisputed ecological and economical importance, mangroves are disappearing worldwide by 0.7 (FAO 2007) to 2% (Lewis 2009) per year, mainly due to aquaculture, urbanization, coastal landfill, pollution, upstream land use (Duke et al. 2007) and harbor development activities.

Brazil has lost at least 50.000 ha of mangroves over the last 25 years, mainly along the southern coast (FAO 2007). If mangrove forest destruction remains at the same pace, a no-net-loss of mangrove areas would require effective restoration of 2,000 ha.year^{-1} and double that amount to bring back what has already been lost (see previous chapter.). As in other locations worldwide, unsuccessful outcomes to restore Brazilian mangroves are habitually related to the inadequate methods used, based on simple planting and repetitive replanting of mangrove propagules/seedlings, rather than initially assessing the reasons for the absence of mangroves, as the reasons why natural recovery had not occurred (Cintrón-Molero 1992; Erftemeijer & Lewis 2000; Field 1998; Lewis 1982; 1990a; 1999; 2000; 2005; 2009b).

Substrates of restored mangroves can present four types of problems related to physical structure and stability, adequate moisture (determined by appropriate tidal fluctuation concomitant with soil aeration), adequate nutrition and lack of toxicity (Mckee & Faulkner 2000), which will in turn determine forest development. Nonetheless, where successfully replanted, periods superior to two decades may be necessary to evaluate restoration's success base on vegetation's structural attributes (Crewz & Lewis 1991; Lugo 1992; Luo et al. 2010). Thus, simple planting success should not be considered ecological restoration, even if it appear to work as perceived from a short-term perspective (Ellison 2000; Lewis 2009), since the time lag required to assess actual functional performance can be longer than the time lag needed to evaluate forest structural traits (Mckee & Faulkner 2000).

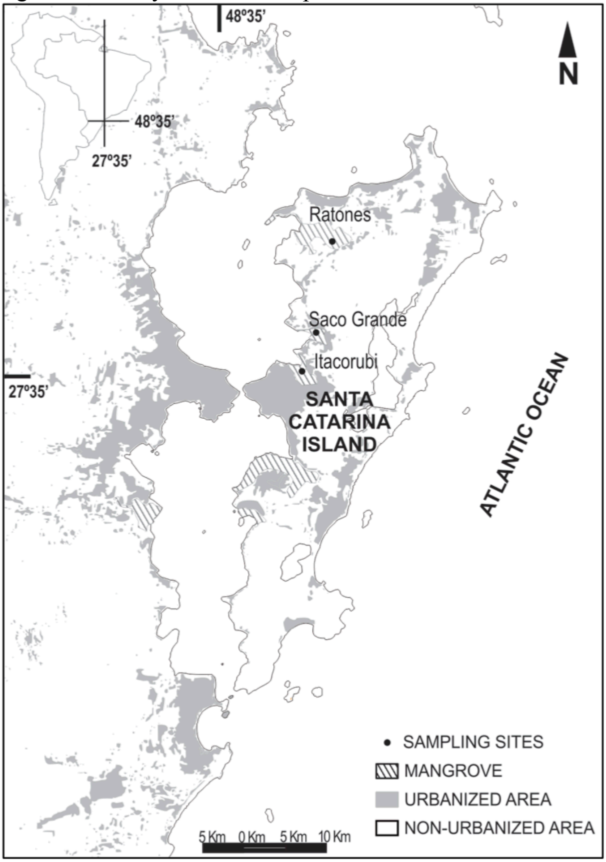
Nevertheless, experimental approaches, coupled with the assessment of exploratory variables, may be reliable tools for the assessment of ecological functions based on forest structure and complexity. In this work we hypothesized that secondary succession on restoration sites that have been managed by single planting of mangrove species may be compromised by residual stressors, thus leveling off ecosystem's structural complexity and functioning at lower stages. To test our assumption we compared vegetation's structural characteristics of three replanted mangrove stands with reference sites within an experimental design context. First, to allow proper comparison as well as verification of trends in secondary succession we selected approximately same age and old-growth natural stands as reference sites. Then, we tested the significance of the differences observed in forest structure and examined the level of correlation between it and the environmental variables investigated aiming to identify which set of variables best explained the patterns observed for forest structure. Finally, we proposed patterns of secondary succession for areas subjected to different stressors, upon which we discussed the potential of recovery of ecosystem's services.

3.3. METHODS

3.3.1. Field sites and sampling strategy

The investigated mangrove stands are nested in three independent watersheds located in Santa Catarina Island, southern Brazil (Fig. 6). The regional climate is sub-tropical humid with no characteristic dry season but with reduced rain volume from April to September (Cruz 1998). The local tide is micro-tidal (Melo et al. 1997) with south and north winds being the main physical agents influencing the local hydrodynamic. Mangroves and salt marshes are located at the estuarine end of these watersheds, which drain upland terrain through meandering rivers that cut light to moderately urbanized short coastal plains (Pagliosa & Barbosa 2006) formed during late quaternary. Considering the latitudinal limit of distribution of the studied mangroves, stands still exhibit structurally well-developed old-growth forests dominated by *Avicennia schaueriana* Stapf & Leechman ex Moldenke interspersed with gaps opened naturally or due to human interferences. This situation enabled the selection of three replanted sites and two different temporal reference sites for them.

Figure 6 – Study area and sample sites.



All of the three restoration areas were managed by single planting about ten to twelve years ago and immediately left to natural regeneration. To allow proper comparison as well as to help to verify any trend, regarding the time since restoration actions took place, two types of reference stands were chosen within each mangrove sub-setting: one consisting of a natural regeneration area, with approximately ten years old and the other being an old-growth mangrove stand (over 50 years). The identification of the reference stands was performed by visual interpretations of historical aerial images complemented by field surveys. Itacorubi restoration's stand suffered a massive mortality event (*sensu* Jiménez et al. 1985) probably caused by toxic landfill leachate from a deactivated landfill sited on top of the landward portion of the mangrove forest six decades ago (Huber 2004). Saco Grande and Ratones restoration's stands had their topography altered by dirt used to fill a housing development area (Huber 2004) and by excavation of material to built aquiculture ponds (Matos 2002), respectively. On those two last mangrove stands, planting was carried out without attempting the reestablishment of the topography.

The experimental design was a 3 X 3 factorial, with locations (Itacorubi, Saco Grande and Ratones mangrove sub-settings) and treatments (restoration, natural regeneration and old-growth stands) as the main factors. Three plots were set to assess forest structure in each treatment-site combination.

3.3.2. Forest structure and environmental data

In each site and treatment we investigate the forest structure and the environmental variables. Forest structure was described on the basis of density and basal area of trees (Cintrón & Schaeffer-Novelli 1984). Plots size varied (6, 25 and 100 m^2) according to forest density, in order to assure homogeneity in terms of structural characteristics (species composition and structural development of individuals). Within the plots all trees above 1-meter in height, alive and dead, were identified to species level and had the diameter at breast height (DBH) and heights (only for the alive ones) measured for each one of its stems. Where stands presented shrub-like structure and branch profusion below 1.3 m (restoration and natural regeneration stands), diameter was measured at 5-15 cm above soil surface.

Interstitial salinity was monitored monthly (may to july 2011). Pore water was obtained from PVC tubes (ø 5 cm; 80 cm in length) perforated at the lower extremity, which were inserted into the sediment to a depth of 40 cm (Cintrón & Schaeffer-Novelli 1984). Salinity was measured with a field refractometer (0.1 psu). Sediment samples of the first 20 cm (from surface) were collected separately for determination of size fractions, organic matter, nutrients (C, N, P) and water content. Because sediments properties can vary widely over tidal, dial and seasonal time-scales, all samples were collected within 1 hour, at the time selected for sampling (Tolhurst & Chapman 2005), for each mangrove sub-setting. PVC cores (ø 5 cm) were used to collect samples for nutrient analysis and plastic containers for the other parameters. Samples were immediately taken to laboratory where they were either kept frozen (samples for nutrient analysis) or processed immediately using conventional methods: size fractions and organic matter (Suguio

1973; Wentworth 1922); water-content (Tolhurst & Chapman 2005); and concentration of C, N (plasma mass spectroscopy; ICP-MS); and P (Áspila et al. 1976) were determined. Topography was measured using a real-time kinematic geographic positioning system. Sediment compactness was measured considering the number of hits needed for complete penetration of a metal rod into the sediment (Alam 1992). Tide data for the year 2011, obtained from Brazilian Navy's Board of Hydrography and Navigation, was used to estimate the average flooding frequency in terms of events, i.e., number of times that the tides exceeded the elevations measured in the field.

3.3.3. Statistical analyses

Forest structural data (species composition; $\overline{DBH}$; minimum, maximum and average height; stems density; basal area; and the relation stems/individual) were used to verify similarity between treatments. distribution pattern was analyzed using multi-dimensional scaling ordination (MDS) on the basis of Bray-Curtis dissimilarity on $\sqrt{}$ transformed data as descriptors. The significance of the differences between sites, treatments and their interactions was evaluated through permutational multivariate analysis of variance (Anderson 2001; McArdle & Anderson 2001), carried out on PERMANOVA program (Anderson 2005). The analysis was made on unrestricted raw permutation data and run 9,999 times. Sites were held as random factors and treatments as fixed. The relationship between environmental variables and forest structural characteristics was explored using Spearman rank correlation between two similarity matrices (Bray-Curtis for biotic data and Euclidean distance for environmental, both on $\sqrt{}$ transformed data), successively testing every possible combination of environmental parameters to indicate which arrangement best explains the observed multivariate community patterns. Both ordination (MDS) and correlation data analyses (BIOENV routine) were performed using PRIMER statistical software (Clarke & Gorley 2006).

3.4. RESULTS

In the reference stands (both natural regeneration and old-growth) Avicennia schaueriana was the dominant species with higher density and basal area values, followed by *Laguncularia racemosa* L. Gaertn. F., Combretaceae and *Rhizophora mangle* L., Rhizophoraceae (Table 2). On the contrary, restoration stands were dominated by *L. racemosa* that outnumbered *A. schaueriana* both in terms of density and dominance, except for one site (Itacorubi), which was dominated by *A. schaueriana*. *Rhizophora mangle* was virtually absent in restoration stands. DBH and average height were at least twice as big in old-growth stands when compared to restoration and natural regeneration stands while these last two presented similar values.

Table 2 - Structural attributes (mean ± SE) of the mangrove forests studied in southern Brazil.

Stand		Species	Density (stems.ha^{-1})	Basal area (m^2.ha^{-1})	$\overline{DBH}$ (cm)	Mean height (m)
ITA	RT	*Avicennia schaueriana*	4333 ± 1115	6,89 ± 2,38	3,14 ± 0,22	3,06 ± 0,16
		Rhizophora mangle	22 ± 22	0,02 ± 0,02		
	RG	*Avicennia schaueriana*	4311 ± 1294	2,27 ± 0,80	2,52 ± 0,17	2,42 ± 0,25
		Rhizophora mangle	44 ± 30	0,02 ± 0,01		
	OG	*Avicennia schaueriana*	844 ± 240	4,12 ± 1,68	9,55 ± 2,00	6,34 ± 0,81
		Laguncularia racemosa	17 ± 12	0,02 ± 0,02		
SG	RT	*Avicennia schaueriana*	800 ± 323	0,81 ± 0,42	2,69 ± 0,16	2,12 ± 0,05
		Laguncularia racemosa	7333 ± 2253	3,37 ± 1,15		
	RG	*Avicennia schaueriana*	2200 ± 688	2,13 ± 0,93	3,02 ± 0,08	2,32 ± 0,13
		Laguncularia racemosa	2133 ± 640	0,81 ± 0,28		
		Rhizophora mangle	378 ± 131	0,12 ± 0,06		
	OG	*Avicennia schaueriana*	417 ± 122	3,80 ± 1,56	8,97 ± 1,09	5,63 ± 0,40
		Laguncularia racemosa	333 ± 130	0,69 ± 0,35		
		Rhizophora mangle	17 ± 9	0,01 ± 0,01		
RAT	RT	*Avicennia schaueriana*	185 ± 185	0,60 ± 0,60	2,55 ± 0,21	2,28 ± 0,24
		Laguncularia racemosa	21852 ± 7991	9,64 ± 4,10		
	RG	*Avicennia schaueriana*	1911 ± 506	3,65 ± 1,16	5,95 ± 1,02	3,96 ± 0,66
		Laguncularia racemosa	1089 ± 262	2,47 ± 0,78		
		Rhizophora mangle	44 ± 30	0,07 ± 0,05		
	OG	*Avicennia schaueriana*	306 ± 77	6,25 ± 2,87	14,66 ± 0,98	9,23 ± 0,67
		Laguncularia racemosa	200 ± 66	0,89 ± 0,26		
		Rhizophora mangle	6 ± 6	0,04 ± 0,04		

ITA, SG, RAT=Itacorubi, Saco Grande, Ratones mangroves; RT, RG, OG= Restoration, Regeneration, Old-growth stands; $\overline{DBH}$=Diameter at Breast Height.

Ordination analysis coupled with permutational analysis of variance showed no differentiation when comparing mangrove sub-settings, but significant differences when treatments were confronted (Fig. 7; Table 3). Pair-wise tests evidenced differences observed among all treatments, except for Itacorubi mangrove where restoration and natural regeneration stands were similar.

Figure 7 – Multi Dimensional Scaling (MDS) ran on overall forest structural attributes of the mangroves studied, southern Brazil. Symbols represent sub-settings (squares=Itacorubi; circles=Saco Grande; triangles=Ratones) and colors treatments (black=restoration stands; white=regeneration stands; gray=old-growth stands).

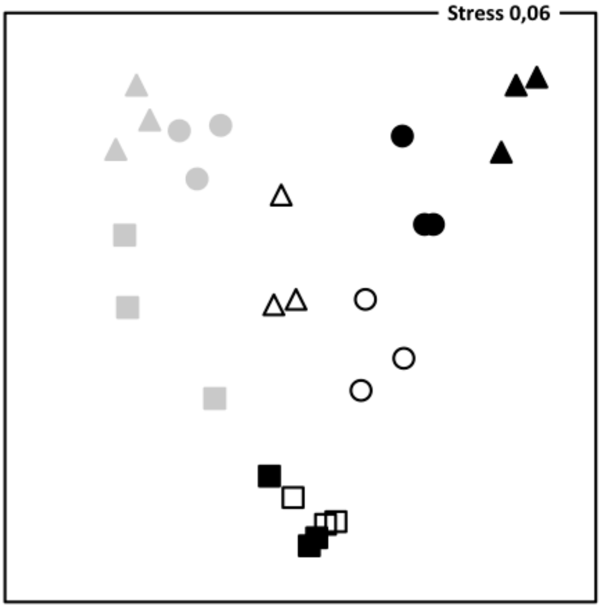
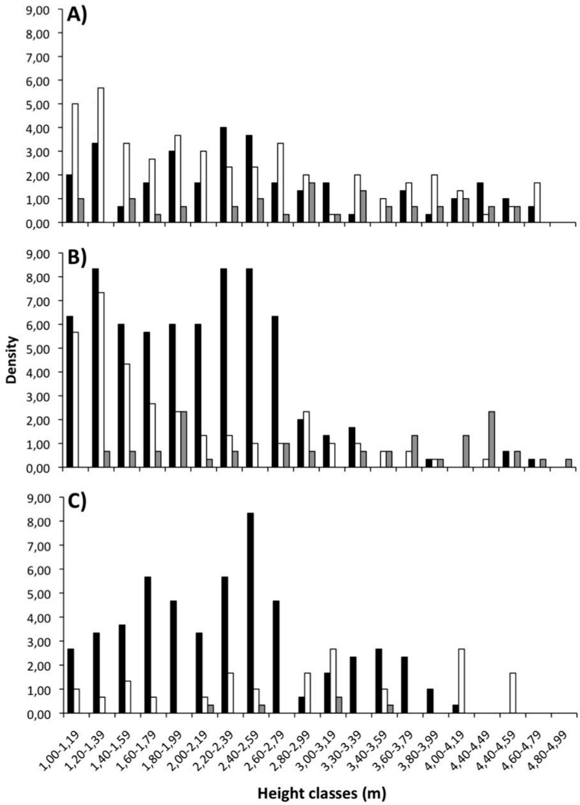


Table 3 - Results of the PERMANOVA and pair-wise comparisons of treatments within the mangroves studied in southern Brazil.

Source of variation	*df*	MS	*F*	P(MC)
Lo	2	5220.8231	3.4263	0.0314
Tr	2	10134.8250	6.6512	0.0016
Lo x Tr	4	1523.7537	7.5152	0.0001
Residual	18	202.7559		
Pairwise tests				
ITA	RT - RG - RF			
SG	RT - RG - RF			
RAT	RT - RG - RF			

PERMANOVA and *post hoc* pairwise comparisons on the basis of the Bray–Curtis dissimilarities on $\sqrt{\ }$ transformed data (same used in the MDS). Lo=locals (Itacorubi, Saco Grande and Ratones); Tr=treatments (restoration, regeneration and old-growth stands). Significant differences at $p < 0.05$ evaluated by permutational t-tests. Underline denotes no significant differences.

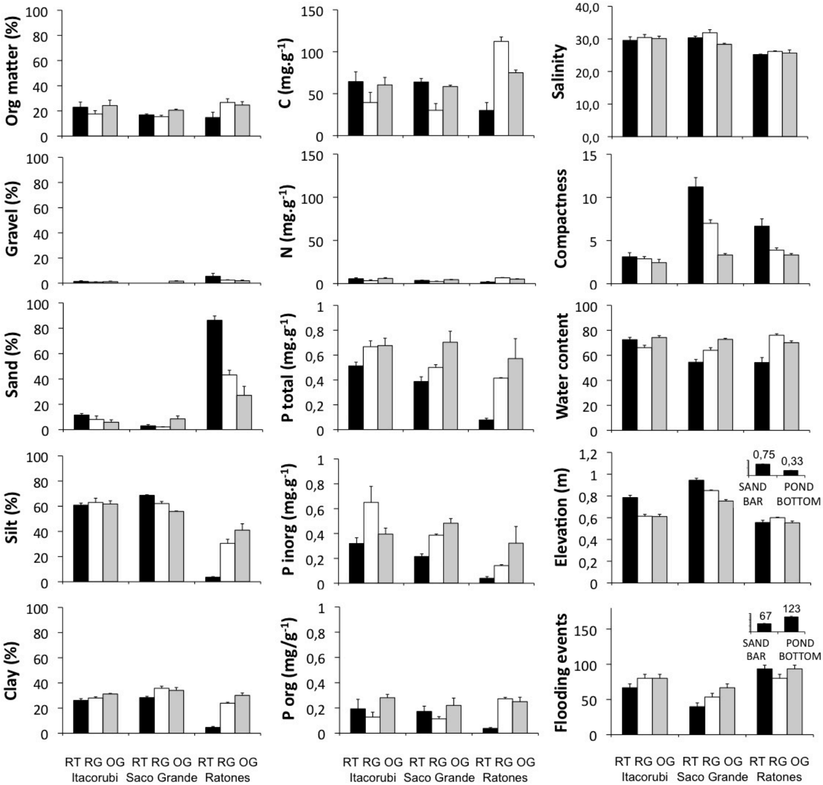
Figure 8 – Number of individuals sorted by classes of height (up to 5 meters in height) in the mangroves studied, southern Brazil. A=Itacorubi; B=Saco Grande; C-Ratones; black=restoration; white=regeneration; gray=old-growth stands.



Although Itacorubi restoration and regeneration stands did not differ in terms of overall structural attributes, the former presented lower densities in its younger cohorts (Fig. 8). Conversely, younger cohorts at restoration stands of the other two sites studied leveled off or surpassed those observed for natural regeneration stands.

Some of the environmental variables also varied considering treatments (Fig. 9). The correlation analysis indicated clay content, interstitial salinity, inorganic phosphorous content, elevation and soil compactness as the set of variables that best explained the pattern of distribution of forest structure observed in the MDS (*pw*=0.521).

Figure 9 – Environmental variables (mean ± SE) investigated illustrating variations between restoration (RT), natural regeneration (RG) an old-growth (OG) stands across the mangroves (Itacorubi, Saco Grande and Ratones) studied in southern Brazil. Details of topographic alterations for Ratones restoration's stand are given on the elevation and flooding events graphics.



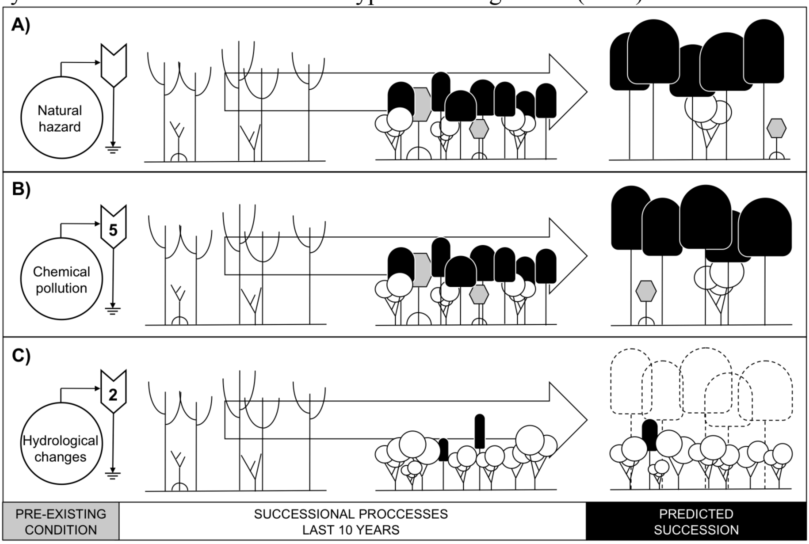
3.5. DISCUSSION

Natural secondary successional process within the studied region is triggered off by *R. mangle*, *L. racemosa* and *A. schaueriana* colonizers. Even though *R. mangle* highly dominates early colonizing stages, the species ratio is inverted as stand matures culminating in well-developed (density and basal area) *A. schaueriana* old-growth stands (Cintrón 1981; Soriano-Sierra 1993). We observed that natural regeneration stands that were colonized by different species, now seem to be developing into a more structural complex organization level dominated by *A. schaueriana*. On restorations stands, where edaphic conditions were physically disrupted, the system seems to have remained arrested in a lower level of structural complexity dominated by *L. racemosa*. This species is known for its suitability in dominating disturbed environments (Menghini 2008; Menghini et al. 2011; Smith III 1992; Soares 1999) and was found in the investigated restoration sites outnumbering *A. schaueriana* and *R. mangle* by far.

Our findings support that the environmental shifts, even after a decade of planting followed by natural regeneration, still favor the persistence of *L. racemosa* hindering progression towards a climax forest form, whereas natural regeneration stands seem to be following the natural secondary succession pattern typical of this latitudinal region. Based on the experiment conducted, we propose a conceptual model of secondary succession for the mangroves studied as a function of the impacts suffered (Fig. 10). When a gap is opened due to a natural impact (i.e., death of an old tree, a lightning strike, wind damage, etc.) secondary succession culminates at old-growth *A. schaueriana* dominated stands (scenario A). At some point a leakage in the landfill (Itacorubi restoration stand) caused the stand's massive mortality. Although, topographic features, mainly related to elevation, were not substantially altered and since such events tend to be episodic, vegetation seems to following patterns of secondary succession similar to those described for natural hazards (scenario B). Where elevation was severely disrupted (Saco Grande and Ratones restoration's stands) secondary succession showed a different pattern. Stand seems to have remained stuck in a lower structural complexity level densely dominated by stunted and bushy *L. racemosa* individuals (scenario C).

In fact, structural data from one of the restoration's stands (Ratones) revealed that the massive planting of *A. schauerianna* propagules (75% of a mixed planting with *R. mangle*; Matos 2002) was in vain, since *L. racemosa* is the dominant species with *A. schauerianna* or *R. mangle* becoming virtually absent. Such altered patterns of secondary succession have been identified for reforested and restored stands ranging from 8 to 18 years old with the prevalence of lower structural complexity stages being attributed to modifications related to substrate elevation (Bosire et al. 2006; Proffitt & Devlin 2005; Shafer & Roberts 2007). Here, the environmental variables evidenced the magnitude of the alterations that occurred in the edaphic compartment, mainly as a reflection of the differences found in elevation. Ground elevation determines flooding frequency and duration, which subsequently affects other sediment characteristics, such as grain size, nutrients contents and sediment compactness, contributing to the variable structure of mangrove forests (Reef et al. 2010). Mangrove forests are very sensitive to edaphic disruptions, mainly to shifts in substrate elevation, and the system's capability to return to a more complex level of organization is strongly affected by the intensity and frequency of the stressor (Cintrón & Schaeffer-Novelli 1983).

Figure 10 – Observed and predicted secondary succession for the mangroves studied according to impacts suffered. A – A gap opened by a natural impact. Secondary succession culminates at old-growth *A. schaueriana* dominated stands. B – Massive mortality is caused probably by a leakage in the landfill (Itacorubi restoration's stand case). Although, topographic features, mainly related to elevation, are not substantially altered. Vegetation follows patterns of secondary succession similar to those described for natural hazards (above). C – Elevation is severely disrupted (Saco Grande and Ratones restoration's stand cases). Forest remains stuck in a lower structural complexity level dominated by *L. racemosa*. Black=*A. schaueriana*; white=*L. racemosa*; grey=*R.mangle*. Symbols used to illustrate stressor types after Lugo et al. (1981).



Despite the fact that Itacorubi restoration and regeneration's stands did not differ in terms of overall structural attributes, a comparison based on the number of individuals sorted by classes of height, representing different cohorts (Jiménez 1990), revealed an inferior regeneration potential for the former, since it presented lower densities in its younger cohorts. Although we did not investigate sediment toxicity, heavy metals on restored stands soils are know for hampering vegetations development (Mckee & Faulkner 2000) and that could be a partial explanation for the particular case of Itacorubi location, considering its cohorts compositions, since the heavy metal contents in its soils are superior to those observed in the other studied locations (Pagliosa et al. 2004a; Pagliosa & Barbosa 2006). Therefore, attention must be drawn to avoid early conclusions, as monitoring periods ranging from 10 through 25 (Crewz & Lewis 1991) to 50 years (Lugo 1992; Luo et al. 2010) may be required to evaluate mangrove restoration success based on vegetative structural characteristics. Additionally, the time lag required to assess ecosystem functionality is longer than the time lag needed to assess survival of the vegetation and the overall structural attributes (Mckee & Faulkner 2000).

Old-growth forests are the high-end manifestation of secondary succession, expressing nature's labor in terms of spatial and time scales. They are the adapted product of genetic, biological and ecological filters and the dynamic environment they occupy (Hooper et al. 2005). Adaptations involve temporal spans in the order of thousands of years to develop the forested landscapes we see today. These mature assemblages develop self-regulation mechanisms that allow them to cope with higher magnitude disturbances and renew themselves throughout time, thus maintaining complexity, functionality and adaptive capacity (Lugo 1978, 1980; Lugo et al. 1981). On the other hand, there is no guarantee that young plantings will develop into mature-like stands and even if they were on track they might not have time to build up enough resilient properties to ensure the stability needed for secondary succession to culminate (Cintrón & Schaeffer-Novelli 1983). Natural regeneration is a continuous process subsidized by persistent recruitment.

Mangrove rehabilitation is possible by quitting the stressors and ensuring the reestablishment of the subsidiary energies, chiefly hydrology (Cintrón & Schaeffer-Novelli 1983; Cintrón-Molero 1992; Lewis 1982, 2005, 2009c, 2011; Lugo et al. 1981). Nonetheless, inobservance of basic mangrove ecological principles, as for the cases studied, may lead to the development of non-analogous, lower complexity adapted forms, with implications on both immediate and long-term, large-scale ecosystem's services. Mangroves have been recently recognized as a key component of the atmospheric carbon cycle, being the most carbon-rich forests in the tropics (Donato et al. 2011; Nellemann et al. 2009). Due to their open system and dynamic nature, mangroves do not conform to the classical concept of forest development and function. Differently from terrestrial vegetation, mature mangrove forests remain net producers of carbon, presenting higher gross primary production/respiration ratios (P_G/R) than younger and more disturbed stands (Alongi 2011; Lugo 1980).

Because the ecological value of old mangrove forests is much greater than restored forests or plantations (Nickerson 1999) and it is in their senescent form that ecosystem services, such as carbon sequestration, peak up, policies must give priority to schemes to maintain their existence (Alongi 2011). It is generally accepted that the capacity of the environment to deliver ecological services needs to be increased rather to maintain. Therefore, restoration projects must be designed to allow the development of systems with analogous complexity and functionality. Because mangrove stands are nested within complex landscapes the stability of higher level of organization must be considered (Schaeffer-Novelli et al. 2005).

At their geographical limits species may have a smaller tolerance to environmental changes, as they have to allocate more resources to deal with limiting factors and climatic stressors. Climate change is an immerging variable that must be taken into consideration. Recent data shows that mangroves are able to cope with sea-level rise (Alongi 2008), however it is still an open question how less developed marginal forests will respond to these increased rates coupled with local stressors and limiting factors including altered atmospheric conditions, triggered by climate change.

3.6. CONCLUSIONS

Although a larger time lag may be required to assess rehabilitation success based on vegetation's structural attributes, the experimental design used allowed the: (1) identification of changes in secondary succession due to residual impacts, and (2) make inferences regarding the fate of structural complexity and functioning. After 10-12 years of planting followed by natural regeneration, restoration sites exhibited secondary succession patterns that differed significantly from adjacent reference sites. This study demonstrated that the isolated planting of single mangroves species targeting for the rehabilitation of degraded areas could be ineffective if site and setting-specific characteristics (topography, pollutants inputs, proximity to propagule points) are not taken into consideration. Nevertheless, to fully validate the interpretation of the findings, long-term assessments must be performed.

Finally, the increased recognition of the mangrove carbon sequestration functions should trigger reconsideration of conventional practices including the time scale used to evaluate outcomes, in order to provide coherence between project life-span and ecological outcomes. Additionally, to avoid the inevitable failure of poorly planned and executed restoration activities and the degradation of the services provided by mangroves are revision of policies and practices that perpetuate mangrove conversion is required as well as the criteria used for establishing compensatory measures and effective rehabilitation is essential. Mangroves restoration-rehabilitation is an essential component of a transition to sustainability and carbon emission mitigation. It is a relatively low cost practice that helps society to establish a balance between short-term resource use and long-term sustainability goals.

4 CONCLUSÃO GERAL

Conclui-se que, em função do reduzido tempo despendido nos monitoramentos, associado a carência de delineamentos experimentais adequados, interpretações consistentes sobre a dinâmica populacional – portanto do sucesso – dos experimentos de plantio realizados no Brasil não são possíveis.

O teste de hipótese revelou que as características estruturais de bosques de mangue replantados há cerca de uma década apresentam diferenças significativas quando comparados a bosques referencias de idade similar.

Por fim, a incorporação de bosques maduros no delineamento permitiu inferir sobre os processos de sucessão secundária, os quais aparentam estar sendo inibidos por tensores residuais nas áreas replantadas, restringindo, portanto, o desenvolvimento estrutural e a complexidade destes bosques. No entanto, para se confirmarem estes padrões, monitoramentos a longo prazo se fazem necessários.

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