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Eleven years of range expansion of two invasive corals (*Tubastraea coccinea* and *Tubastraea tagusensis*) through the southwest Atlantic (Brazil)

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ABSTRACT

We report on the temporal and spatial changes in populations of the invasive corals *Tubastraea coccinea* and *Tubastraea tagusensis* over an eleven year period at the Ilha Grande Bay, tropical southwest Atlantic. A semi-quantitative method was used to investigate the geographical distribution of the two congeners on subtidal rocky reefs along 350 km of coastline by applying a relative abundance index (RAI) to quantify change. Data were compared among 2000, 2004, 2010 and 2011. The indices showed a transition from rarity to dominance throughout the region as well as range expansion; in contrast at one site, where a pilot management initiative of manual control has been carried out, there was a reduction in abundance over time. Abundance values were compared to distance from possible points of introduction to pinpoint where the initial introduction occurred. The observed relationship between the possible points of entry and abundance of the two *Tubastraea* species was highly significant for the achorage and oil terminal whereas somewhat less so for the shipyard and port. The data obtained in this study are being used to plan further urgent management actions to control the biological invasion of the two *Tubastraea* species throughout the region, as well as being applied in modeling the range expansion into other regions.

1. Introduction

The rates and pathways by which species move around the planet have been completely modified by human action (Vitousek et al., 1987). Shipping contributes to the elimination or reduction of the natural barriers that have always delimited marine ecosystems, increasing homogenization of marine flora and fauna worldwide (Silva and Souza, 2004). The successful establishment of marine invasive species is largely due to the transport of ballast water, and fouling on ships, platforms and floating objects (Carlton and Geller, 1993; Carlton, 1996). Regardless of the pathways and mechanisms involved in the process of introduction, invasive species can transform the structure and function of an ecosystem by creating novel interactions, or by changing fluxes of material and energy through the system.

Tubastraea coccinea Lesson, 1829 and *Tubastraea tagusensis* Wells, 1982 (Anthozoa; Dendrophyllidae) are considered to be the first scleractinian corals to have invaded the southern Atlantic, in what is an uncommon two-species marine introduction. They are azooxanthellate, not depending directly on sunlight for their development, and can frequently be found in shaded places like caves, overhangs and beneath boulders on subtidal tropical rocky shores and reefs (De Paula and Creed, 2005). *T. coccinea* is now considered to be a cosmopolitan species (Cairns, 1994). *T. tagusensis* was first described in the Galapagos Archipelago (Wells, 1982) but has also been recorded from Nicobar Islands (Cairns, 2000), Palau (Cairns, 2000) and Kuwait (Hodgson and Carpenter, 1995). Both are considered non-indigenous and invasive along the Brazilian coast (De Paula and Creed, 2004), and *T. coccinea* has also been considered invasive in the Caribbean (since 1943, in Puerto Rico and

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Curacao, Cairns, 1994, 2000, Sammarco et al., 2010). *T. coccinea* subsequently dispersed throughout the Caribbean, and is found on oil rigs in the Gulf of Mexico and on hard grounds in Florida (Fenner and Banks, 2004). *T. tagusensis* is considered exotic to the Brazilian coast (De Paula and Creed, 2004). Another species of the genus, *Tubastraea micranthus*, was recently found on a single platform in the northern Gulf of Mexico (Sammarco et al., 2010), but has not yet been reported in Brazil.

In Brazil, these invaders are widely distributed, with records of expansion into new areas including several Marine Protected Areas (Silva et al., 2011). The first record of the species on the Brazilian coast occurred in the 1980s, on oil and gas platforms belonging to Petrobras in the Campos Basin, north of the state of Rio de Janeiro (Castro and Pires, 2001). In the 1990s the genus was reported on the rocky shores of the Ilha Grande Bay (De Paula and Creed, 2004). Today, records have extended the occurrence to São Paulo (Mantelatto et al., 2011), Espírito Santo, Santa Catarina (Silva and Barros, 2011) and Bahia States (Sampaio et al., 2012), along 2000 km of coastline as well as at least 20 oil platforms, drilling ships and floating, storage and offloading ships and mono buoys.

As they are ecosystem engineers, once established *Tubastraea* spp. alter community structure and function (De Paula 2007). According to Creed and De Paula (2007), *Tubastraea* spp. did not show significant selection for specific substrate types, which may contribute to their success in invading new areas. These corals also have reproductive characteristics typical of opportunistic species, such as high oocyte production, precocious reproduction age, short embryo incubation time and hermaphroditism (De Paula, 2007). The secondary metabolites produced by these species provide an additional strategy which may facilitate their colonization and expansion. Recent studies have shown that *Tubastraea* spp. produce substances with anti-fouling and anti-predation properties (Lages et al., 2010), besides releasing allelopathic substances capable of causing tissue necrosis in the endemic coral *Mussismilia hispida* (De Paula, 2007; Lages et al., 2012). These characteristics ensure that once established *Tubastraea* spp. can become the dominant benthic organisms (De Paula 2007), overwhelming native species and altering the dynamics of ecosystems that have been invaded (Lages et al., 2011). High cover of these species of *Tubastraea* changes ecosystem functions compared to the more usual communities of macroalgae and zooxanthellate cnidarians typical of these shores; the community becomes heterotrophic rather than autotrophic (Lages et al., 2011).

In order to best employ management strategies that can be used to ameliorate marine biological invasions it is first necessary to quantify change in the abundance of the populations over time and space in order to determine the rate of increase in abundance and predict the rate and possible consequences of range expansion. Here we report eleven years of monitoring the distribution and abundance of the corals *Tubastraea tagusensis* and *Tubastraea coccinea* at the ground zero of the biological invasion of these species in the Southwest Atlantic.

2. Materials and methods

2.1. Study area

The Ilha Grande Bay (IGB) (22° 50′– 23° 20′ S and 44° 00′ – 44° 45′ W) is located in the south of the state of Rio de Janeiro, southeastern Brazil, and has about 350 km perimeter on the waterline (Creed et al., 2007). The region has a high throughput of marine traffic including ships and oil platforms under transport, because of the presence of two ports, an oil terminal, shipyards and an anchorage (De Paula, 2007).

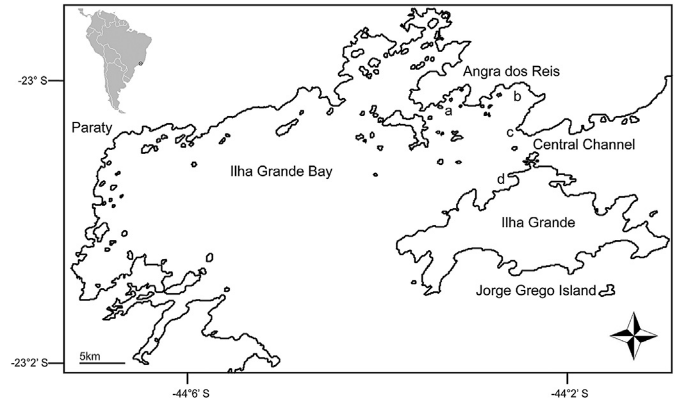

Fig. 1. Map of the region of Ilha Grande Bay, Rio de Janeiro, Brazil, with the possible points of entry of *Tubastraea* spp.: a) Port of Angra dos Reis, b) BrasFels Shipyard c) Petrobras Ilha Grande Bay Oil Terminal (TEBIG), d) Bananal Anchorage.

2.2. Monitoring

The field studies were carried out in winter 2000, autumn-winter 2004, winter 2010 and spring 2011. We used a fast, easily repeatable semi-quantitative method to carry out extensive mapping of the distribution of *Tubastraea coccinea* and *Tubastraea tagusensis* (De Paula and Creed, 2005) at 144 locations. Fieldwork study locations were distributed approximately equidistantly along the coastline and islands of the region to generate a homogenous sampling effort but the exact study sites were chosen haphazardly from nautical charts with coordinates then fed into a GPS for location in the field. At each site two snorkelers swam parallel to the shore, estimating the density of each species of *Tubastraea* independently. Each diver conducted five transects, spending about 1 min recording per 25 m transect. Data recorded were relative abundances using the "DAFOR" scale proposed by Sutherland (2006): Dominant, when populations *Tubastraea* spp. are extremely apparent, frequently occupying areas >1 m^2; Abundant, when *Tubastraea* spp. occurred frequently forming patches of 10–50 cm diameter; Frequent, numerous isolated colonies or small patches of up to 50 cm in diameter; Occasional, when 5–10 colonies or small groups were counted per 1 min dive; Rare, when one-to-five colonies were counted in 1 min; Absent, not seen during the 1 min dive (Sutherland, 2006; Silva et al., 2011). These observations were transformed to a quantitative relative abundance index (RAI) by assigning a scale from 10 (dominant), 8, 6, 4, 2 to zero (absent); a mean of the total of ten transects was calculated.

2.3. Data analysis

As initially we did not know that two different species co-occurred, in 2000 we quantified abundance only at the genus level (De Paula, 2002). The 2004 data were a compilation of data collected in a separate study using identical methods during a Rapid Assessment of Marine Biodiversity – Marine RAP (Creed et al., 2007) supplemented by personal unpublished observations of A.F. De Paula. In order to calculate change over time we used only those locations which were repeatedly monitored (70 sites).

We generated maps (Surfer 8 Golden Software) by using interpolation (Kriging) to show the relative abundance and distribution of two species of *Tubastraea* throughout the region. In order to compare change over the 11 years at the genus level, we conservatively used the higher value of the paired species abundance observations in each transect at each location to estimate the genus

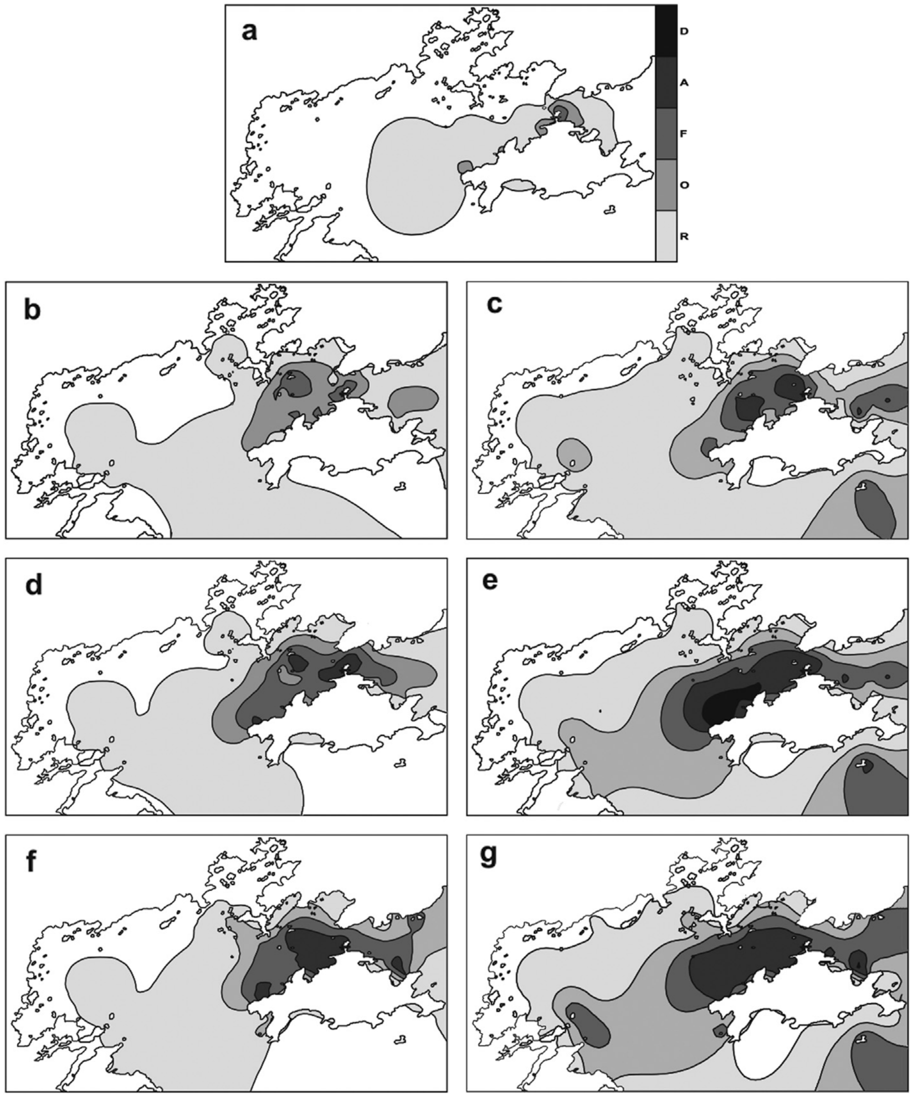

Fig. 2. Map of distribution and abundance of the *Tubastraea* spp. from to 2000 to 2011 in the Ilha Grande Bay (n = 144). a) *Tubastraea* spp. in 2000; b) *T. coccinea* in 2004; c) *T. tagusensis* in 2004; d) *T. coccinea* in 2010; e) *T. tagusensis* in 2010; f) *T. coccinea* in 2011; g) *T. tagusensis* in 2011.

level location mean for 2004, 2010 and 2011, and thus obtained genus level abundance. In order to describe range expansion rates we investigated abundance over time throughout the region by calculating the relative frequency in abundance classes. Furthermore, we calculated and compared abundance of *Tubastraea* at 25 locations (which had *Tubastraea* monitored at all four sample times).

To identify the most probable of four hypothetical points of introduction A) Angra dos Reis Port, B) BrasFels shipyard, C) the Petrobras Baia de Ilha Grande Oil Terminal (TEBIG), D) Bananal anchorage (where oil platforms stop for repairs or maintenance or while awaiting docking at the BrasFels shipyard), (Fig. 1), we assumed that the highest abundance of the corals would be found nearest the point of introduction. We used cubic model regressions for curve estimation as a predictive tool (using R^2 values) to identify the strongest (negative) relationship between abundance and distance from each of the four probable points of entry. We used the 2011 dataset from which we calculated mean values of all points at 2.5 km distance intervals from each hypothetical point of introduction. Curve fitting and testing were carried out using IBM SPSS Statistics v19 software.

3. Results

Tubastraea spp. expanded their range and abundance over the eleven years studied at an estimated rate of 2.1 km per year, mainly into the west of the Ilha Grande Bay. In 2000 *Tubastraea* spp. were registered at 30 sites, all of which were located on Ilha Grande or close-by islands. The highest RAI (equivalent to "frequent") was found in the Central Channel between Ilha Grande and the mainland. Three small regions to the west of Ilha Grande had a RAI equivalent to occasional (Fig. 2a). From 2004 to 2011, when the species were quantified separately, *Tubastraea tagusensis* always had higher RAI than *Tubastraea coccinea* (Fig. 2b–g). In 2004, 31 sites had *T. coccinea* and 35 had *T. tagusensis* (Fig 2b and c). While *T. coccinea* was more restricted to the western Central Channel (RAI ≈ "common"), *T. tagusensis* was abundant in the western Central Channel, frequent at Jorge Grego Island south of Ilha Grande and occasional in the west of Ilha Grande Bay (Fig. 2c).

In 2010 *T. coccinea* was observed at 65 sites and *Tubastraea tagusensis* at 73. *Tubastraea coccinea* was frequent throughout the west of Ilha Grande and the islands in the Central Channel (Fig. 2d and e). *T. coccinea* was abundant on the western tip of the Ilha

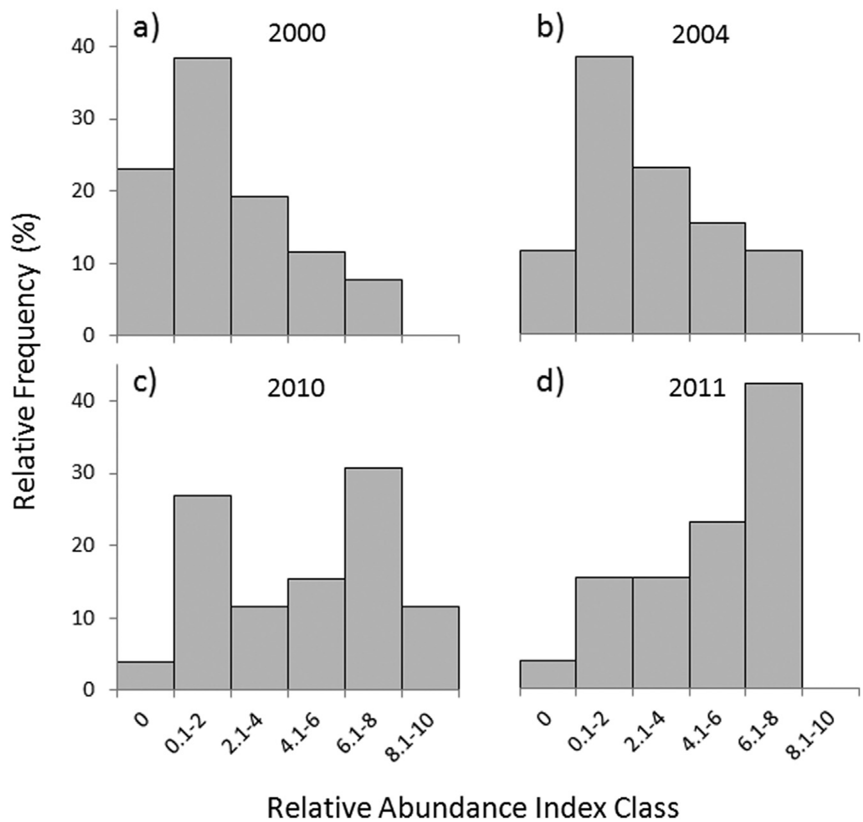

Fig. 3. Change in the frequency of the Index of Relative Abundance of *Tubastraea* at 25 locations in southeast Brazil from 2000 to 2011.

Grande, near the Bananal anchorage and west of the Central Channel. The patterns for *T. tagusensis* were similar to those in 2004, although this invader was now observed covering the entire Central Channel and Jorge Grego Island (occasional and frequent-to-dominant on the western tip of the Ilha Grande) (Fig. 2e). In 2011 *T. coccinea* remained present at 65 points already registered, whereas *T. tagusensis* increased its distribution from 73 to 78 locations. Both species showed increases in the RAIs compared to the

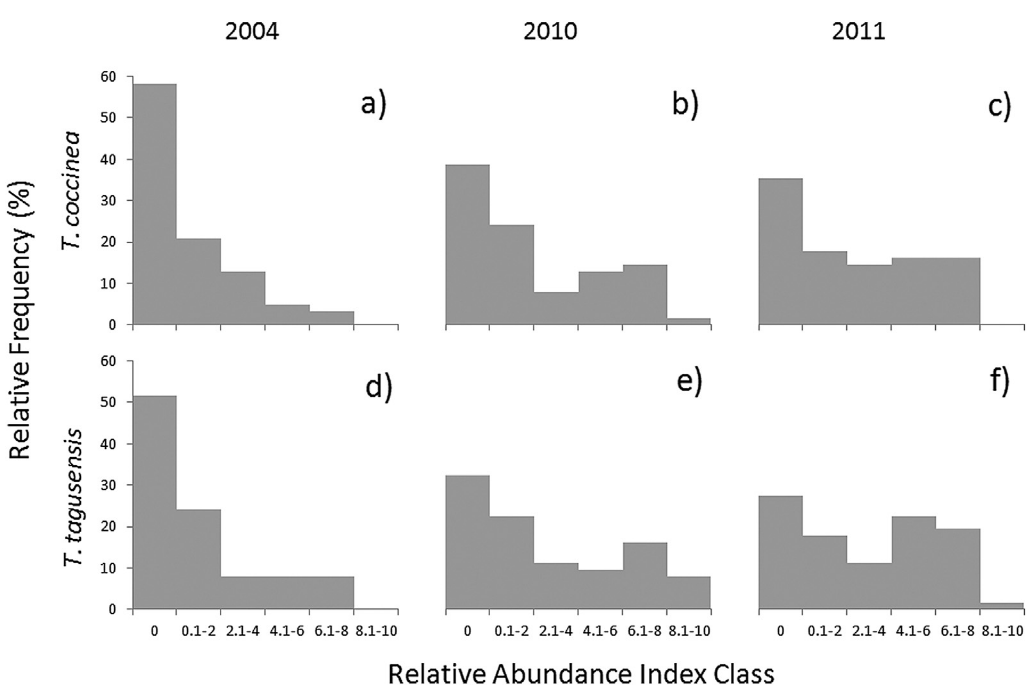

Fig. 4. Change in the frequency of the Index of Relative Abundance of *T. coccinea* (a), (b) and (c) and *T. tagusensis* (d), (e) and (f) at 63 locations in southeast Brazil, from 2004 to 2011.

year before, with the exception of *T. tagusensis*, which showed a decrease from dominant to abundant in a region on the north of Ilha Grande.

The analysis of the relative frequency of corals estimated by the abundance index (RAI) at the 25 sites monitored at all four times (genus level), demonstrated a shift over time for most locations (60%) having RAI equivalent to absent or rare in 2000 to most (≈40%) having RAI equivalent to dominant or abundant in 2011 (Fig. 3). The analysis of the relative frequency of abundance indices at the species level, (2004–2011) at 63 sites sampled at these times showed, over time: 1) a reduction in the number of locations were *Tubastraea coccinea* was absent; 2) a reduction of locations were *Tubastraea tagusensis* was absent and rare; 3) an increase in locations where both species where frequent or abundant (Fig. 4).

Over the eleven years of monitoring in Ilha Grande Bay, the abundance of *Tubastraea* spp. increased at all the locations except two (from between 0.1 and 0.6 RAI units); at Ilha do Macedo there was no change in infestation and at Ilha dos Macacos there was a reduction (Fig. 5).

The analysis used to identify the probable point of introduction showed significant negative relationships between the greatest abundance of *Tubastraea* spp. and the distances from potential points of introduction (Table 1; Fig. 6), although the relationships between the abundance and distance from Bananal Anchorage and

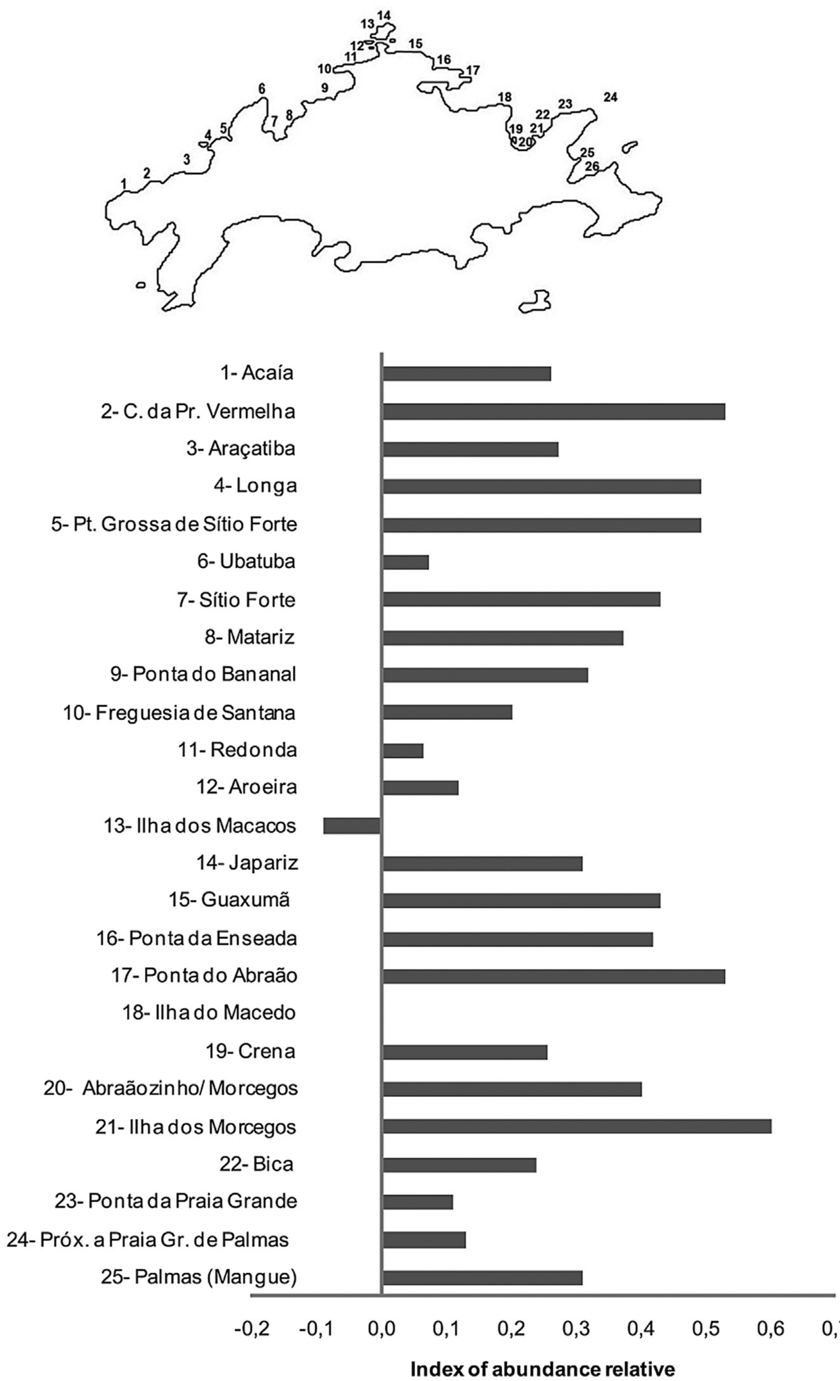

Fig. 5. Change of the Index of Relative Abundance of *Tubastraea* at 25 sites monitored between 2000 and 2011.

Table 1
Description and analysis of curves fit to distances from four potential introduction sites and the abundance of the invasive corals *Tubastraea coccinea* and *T. tagusensis*. Abundances were determined by a relative abundance index and data were mean abundance values of all points at 2.5 km distance intervals from each hypothetical point of introduction. Equations and statistics are for curves fit by cubic model regression.

Site	Species	Regression equation	*ANOVA*		p
			R^2	F	
Bananal Anchorage	*T. coccinea*	$y = -0.0001x^3 + 0.0163x^2 - 0.6213x + 7.6756$	0.97	154.43	<0.001
Bananal Anchorage	*T. tagusensis*	$y = -8E\text{-}05x^3 + 0.0115x^2 - 0.5117x + 7.5292$	0.95	104.06	<0.001
Petrobras Oil Terminal	*T. coccinea*	$y = -5E\text{-}05x^3 + 0.0082x^2 - 0.4025x + 6.2188$	0.94	89.99	<0.001
Petrobras Oil Terminal	*T. tagusensis*	$y = -1E\text{-}05x^3 + 0.0043x^2 - 0.3008x + 6.0927$	0.89	43.85	<0.001
BrasFels shipyard	*T. coccinea*	$y = 0.0003x^3 - 0.0229x^2 + 0.3991x + 1.3289$	0.63	9.516	0.001
BrasFels shipyard	*T. tagusensis*	$y = 0.0003x^3 - 0.0225x^2 + 0.4038x + 1.7211$	0.68	12.27	<0.001
Angra dos Reis Port	*T. coccinea*	$y = 0.0003x^3 - 0.0222x^2 + 0.3774x + 1.0943$	0.81	21.33	<0.001
Angra dos Reis Port	*T. tagusensis*	$y = 0.0003x^3 - 0.0222x^2 + 0.4249x + 0.9424$	0.76	15.48	<0.001

TEBIG Petrobras Oil Terminal were strongest for both species (Fig. 6a and d). In contrast the regular decrease in coral abundance with greater distance was not found for either BrasFels shipyard or Angra dos Reis Port (Fig 6b and c) as coral abundance was lower close by both sites (<5 km), peaked at intermediate distances (≈10 km) and then fell away again. Thus the coefficient of determination was higher for the Bananal anchorage and the Petrobras TEBIG terminal than the BrasFels shipyard and the Port of Angra dos Reis (Table 1).

4. Discussion

These pest corals are now distributed over large areas, with the greatest abundance nearest the probable point of entry at Bananal anchorage. The consolidation of dense populations of *Tubastraea* spp. in Brazil reflects the settlement of larvae (planulae) which occurs in response to the stimulus of presence of conspecific juveniles and adults (Fadlallah, 1983; Carlon and Olson, 1993; personal observations, JCC), combined with the fact these species are able to utilize diverse substrates (Creed and De Paula, 2007; De Paula, 2007). In 2000, *Tubastraea* spp. were absent in parts of the region where rocky shores were highly exposed to wave action, with steep slopes and a dominance of coralline algae "barrens" and sea urchins (De Paula and Creed, 2005; Creed and De Paula, 2007). However, as the range expansion continues, even these shores are becoming invaded, as is the case of the southern part of the Ilha Grande.

The overall range occupied and abundance of *Tubastraea tagusensis* was greater than that of its congener *Tubastraea coccinea*. *T. tagusensis* is precocious. Studies of the reproductive biology of

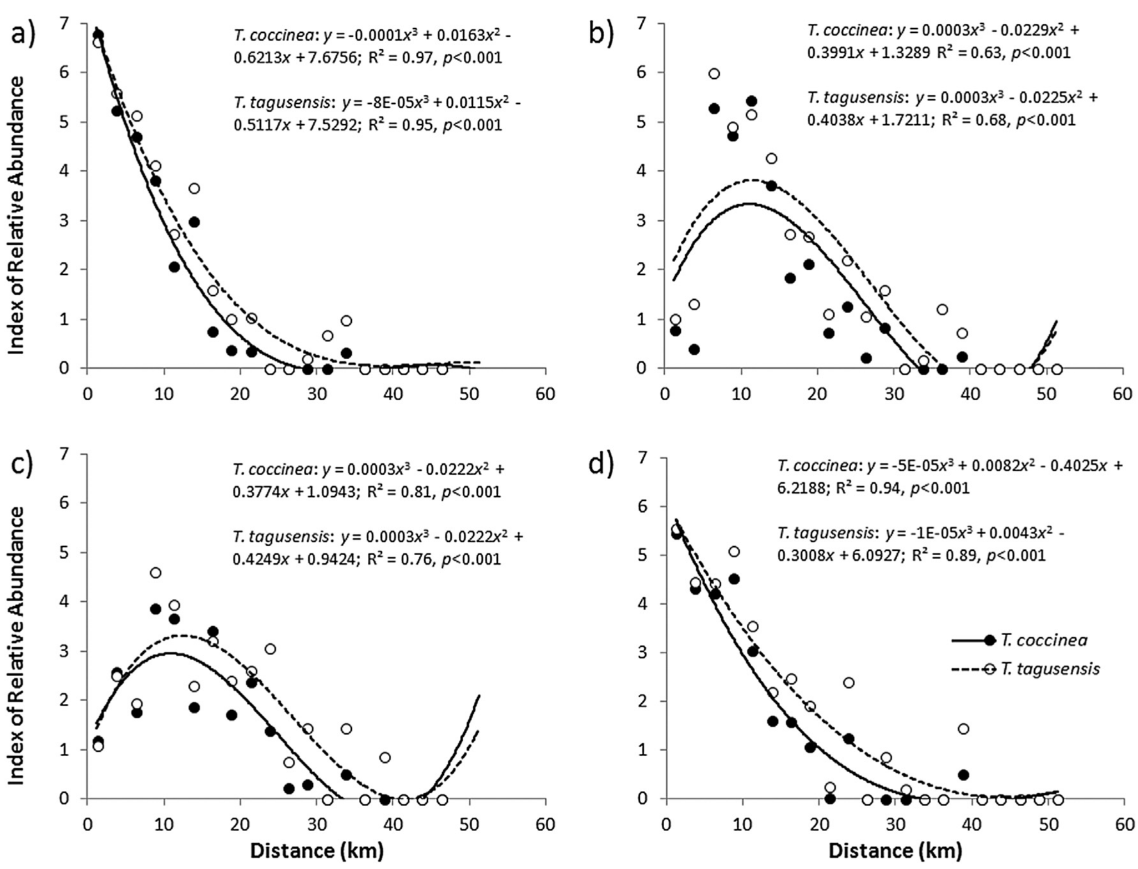

Fig. 6. Relationship between distance from the potential point of introduction and abundance of *Tubastraea* spp. a) distance from Bananal Anchorage; b) distance from the Brasfels shipyard c) distance from the Port of Angra dos Reis d) distance from the Petrobras oil terminal. Equations are curves fit by cubic model regression to mean values of points at 2.5 km intervals.

Tubastraea spp. have described oocytes in colonies with only 3 polyps, 2 months and 20 days old (De Paula, 2007), while Fenner and Banks (2004) reported that *T. coccinea* only initiates the release of the larvae after about 18 months of age. This feature will facilitate the faster spread of *T. tagusensis* and ensure higher abundances. Furthermore, the planulae of these corals are highly buoyant, swimming actively through ciliary movements (Mizrahi, 2008) and the larvae of *T. tagusensis* have been shown to be viable for up to 18 days, in contrast to those of *T. coccinea* which are viable for up to 14 days (De Paula, 2007). In another study it was observed that the abundance of propagules of *T. tagusensis* was also greater than *T. coccinea* on different substrates, such as granite and cement (Creed and De Paula, 2007); all these features allow *T. tagusensis* to expand more effectively through the rocky reefs.

The rate of change in the index of relative abundance was lower at sites close to possible points of entry and greater at more distant locations. These observations confirm that 1) the anchorage of Bananal is the site with the oldest colonization and so is the probable point of introduction; 2) that these invasive corals increase their populations at significantly faster rates near the expansion front than in places that have been invaded for some time – this is due to the effect the carrying capacity has on all expanding populations - most species have high population growth rate initially, but this rate decreases with time, and the population size tends to stabilize (Gotelli, 2008). It is not uncommon to see-boom–bust cycles in invasive marine invertebrates, such as oysters and mussels, which have short life cycles and fast growth rates. However, thirty years into the biological invasion of *Tubastraea* spp. in Brazil, this is evidently not the case for these corals. We did find one case of “negative growth” at Macacos Island, which can be explained by the fact that a pilot study of manual control has been implemented at this area. The Sun-Coral Project, which involves local stakeholders, is currently the only management initiative to control established marine invasive species in Brazil, and the data presented here attest to the effectiveness of the control to reduce propagule pressure and slow-the-spread of these noxious corals. One other location, where abundance hardly changed, was the Island of Macedo, which is nearby the main population center of human population. This site experiences multiple negative environmental impacts, including a sewerage outfall and high turbidity, resulting in low biodiversity.

The Bananal Achorage regularly receives oil platforms for anchorage before docking at the shipyard or when they stop there to carry out sea trials after leaving the shipyard. Our observations only partially corroborate the data of De Paula and Creed (2005), who identified the BrasFels Shipyard and the Petrobras Terminal as potential points of entry; in their study the Bananal Achorage was not considered, although it was mentioned as an alternative possible point of introduction.

The data from Paraty, in the west of the region, were excluded from these analyses as they may be treated as a secondary introduction and as such an outlier, not linked to the first introduction. Moreover, the arrival of *Tubastraea tagusensis* at Jorge Grego Island, on the open ocean side of Ilha Grande, could be the result of the action of currents or small boats that often use the island as a safe haven during storms (De Paula, 2007). Despite these possibilities, to date in Brazil the corals have only been registered on one small boat, which had been abandoned in a marina within the invaded region because it was not seaworthy.

The corals *Tubastraea* spp. have invaded and consolidated their range throughout most of the Ilha Grande Bay, a highly successful marine biological invasion (Colautti and Hugh, 2004; De Paula, 2007). This successful invasion is a result of the initial association with a transportation vector (oil platforms) by a species with wide tolerance to environmental conditions encountered both during transit and upon entering the new ecosystem (Ruiz and Carlton, 2003; De Paula and Creed, 2005). After arrival, due to their precocious reproduction, the *Tubastraea* spp. have established and expanded, causing modification and impact throughout the region. This study is important as it is the first to evaluate the historical distribution and abundance of *Tubastraea* spp. over the long term. As the same species have now been reported as established at seven other distinct locations, the expansion reported here will serve to model range expansions in other regions and thus provide data for management options and control of these marine invasive species. Despite a delay in implementation, the management response to the problem at Ilha Grande Bay has been shown to produce measurable positive effects on propagule pressure, so rapid response and vigorous proactive control, coupled with eradication of smaller populations should be applied to both this and other regions immediately.

Acknowledgments

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