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Research Article

The Sun-Coral Project: the first social-environmental initiative to manage the biological invasion of *Tubastraea* spp. in Brazil

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Editor's note:
This study was first presented at the 9th International Conference on Marine Bioinvasions held in Sydney, Australia, January 19–21, 2016 (http://www.marinebioinvasions.info/previous-conferences). Since their inception in 1999, ICMB series have provided a venue for the exchange of information on various aspects of biological invasions in marine ecosystems, including ecological research, education, management and policies tackling marine bioinvasions.

Abstract

In the 1980s two invasive azooxanthellate corals, *Tubastraea coccinea* Lesson, 1829 and *Tubastraea tagusensis* Wells, 1982 (Dendrophyllidae) invaded the Southwest Atlantic. In Brazil, they were first reported from fouling on oil platforms' and have expanded their range along 3,500km of the coastline. The Sun-Coral Project (PCS) was launched in 2006 as an outreach program aimed at the restoring marine ecosystems, mitigating the environmental damage and redressing the social and economic impacts caused to coastal communities by the sun corals. We train collectors to manually remove the corals from the seabed and earn extra income by selling the skeletons, which are used in craftwork sold to tourists. Engaging human coastal communities in management allowed it to contribute to local sustainable development. The aim of this study was to critically evaluate the first ten years of PCS as a management initiative. We 1) analysed the contribution of PCS to scientific knowledge by carrying out a systematic literature search; 2) reviewed the contribution of the regional and community monitoring program to management planning; 3) analysed management results; 4) identified social-economic effects of extra-income; 5) synthesized information regarding the structure of PCS and the role of environmental education, capacity building, training and communication. PCS is structured into training, environmental restoration, extra income and sustainability, communication, monitoring and research programs. Environmental education is present across all programs. A hotline receives new records, a task force is available for first response management and training, a Visitor's Center was created for communication and as a field base, and a National Sun Coral Records Database was created to gather all information. The PCS Database compiled historical records and demonstrated that the sun corals continued to expand along the Brazilian coastline during the study period (2006–2016). PCS's Research, Development and Innovation (R&D&I) Network (14 institutions, 35 members) contributed to knowledge producing 70% of publications dealing with the sun corals in Brazil. Monitoring was able to map distribution and range expansion at 326 monitored sites over four regions. Twenty five different types of outreach actions were identified which directly affected 143,000 people. Two hundred and thirty thousand sun-coral colonies (8.5 T) have been manually removed through 165 control and eradication actions. Eighty six percent of the 22 collectors and their 80 family members said their lives improved due to the extra income. The results presented here demonstrate that PCS has created a science-based, community supported, conservation initiative which provides information for government, the scientific community and stakeholders, as well as extra-income, methods and human resources for monitoring and managing the sun corals invasion.

Key words: control, environmental education, eradication, extra income, management, monitoring, sun corals

Introduction

Biological invasions are recognized as a major threat to marine and coastal ecosystems (Bax et al. 2003). Invasive species have the potential to cause change in ecosystems resulting in loss of biodiversity, decline of native and commercial species and changes in the function and structure of communities and ecosystems (Carlton 1985; Carlton and Geller 1993; Ruiz et al. 1997; Mack et al. 2000). They may also increase costs or loss of livelihood (Pimentel et al. 2005) which may cause social impacts.

In Brazil the Ministry of the Environment considers 58 marine species to be non-indigenous (NIS) of which nine are listed as invasive (Lopes et al. 2009): two phytoplankton (diatom *Coscinodiscus wailesii* Gran and Angst, 1931; dinoflagellate *Alexandrium tamarense* (Lebour) Balech, 1995); a green macro-algae (*Caulerpa scalpelliformis* (R. Br. Ex Turner) C. Agardh var. *denticulata* (Decaisne) Weber-van Bosse, 1898); two corals (*Tubastraea coccinea* Lesson, 1929 and *Tubastraea tagusensis* Wells, 1982), two bivalves (*Isognomon bicolor* (C.B. Adams, 1845) and *Myoforceps aristatus* (Dillwyn, 1817)) one crab (*Charybdis hellerii* (A. Milne-Edwards, 1867)) and one ascidian (*Styela plicata* (Lesueur, 1823)). From 2008 to 2015, 15 more NIS have been reported but these were not necessarily new introductions: some had previously been considered native or cryptogenic (i.e. of unknown or uncertain origin) whereas one sponge considered NIS was re-classified as cryptogenic. Therefore, the updated number is 72 alien species on the Brazilian coast (Junqueira, unpublished data).

Sun coral (*coral sol* in Portuguese) is the popular name given to species of the genus *Tubastraea*. *Tubastraea coccinea* and *T. tagusensis* (Scleractinia: Dendrophylliidae) are the first scleractinian corals that are NIS in the Southwest Atlantic (de Paula and Creed 2004). They are native to the Pacific and Indian Oceans, and Pacific Ocean, respectively, but while *T. coccinea* has a widespread distribution *T. tagusensis* has a small native range (Galapagos archipelago) (Carlos-Júnior et al. 2015a, b; Creed et al. 2016).

The genus *Tubastraea* is azooxanthellate and was first reported in Brazil in the 1980s as fouling organisms on oil and gas platforms in the Campos Oil Basin, off the State of Rio de Janeiro (Castro and Pires 2001). The two sibling species which have been reported for Brazil (de Paula and Creed 2004) co-occur to the extent that their colonies may grow on one another and intermingled. At the end of the 1990s the sun corals began to invade native communities on rocky shores at Ilha Grande Bay, State of Rio de Janeiro, a region considered to be relatively biodiverse for Brazil (Creed et al. 2007). The region has intense movement of oil platforms and other shipping due to the presence of a shipyard, docking facilities, an oil terminal and anchorage, the latter being the probable first point of introduction to the Brazilian coast (Silva et al. 2014). Subsequently they have established on and invaded tropical and sub-tropical rocky shores and coral reefs along the Brazilian coastline and are expanding their range (Ferreira 2003; Mantelatto et al. 2011; Sampaio et al. 2012), including into marine protected areas (Silva et al. 2011). They have also been found on numerous mobile artificial structures that can act as vectors, such as oil or gas rigs, drilling ships, monobuoys and riser support buoys (Creed et al. 2016; Figure 1). Where established they are also increasing their abundances over large areas (Silva et al. 2014). Currently the sun corals occur in 21 coastal municipalities and have also been recorded on 25 mobile artificial structures and three shipwrecks along more than 3,500 km of the Brazilian coastline (Creed et al. 2016). The invasion history of *T. coccinea* includes, besides the Brazilian coast, the

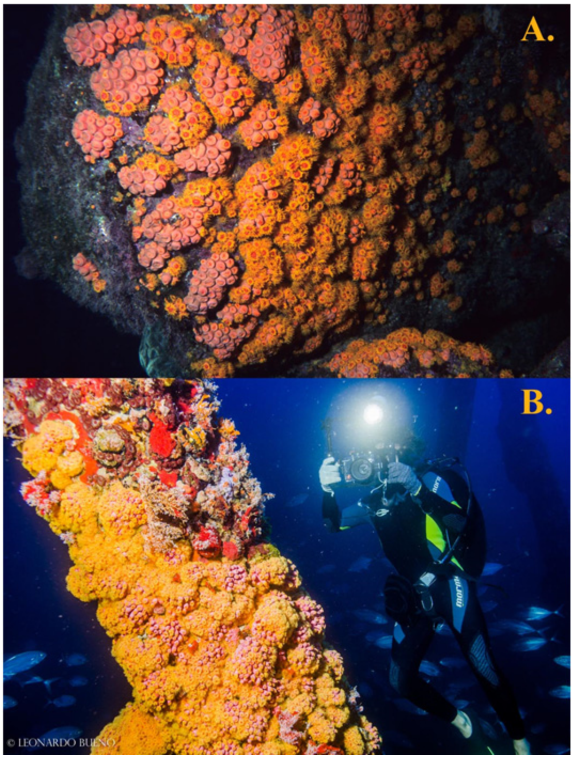

Figure 1. The sun corals (*Tubastraea* spp.) A) *Tubastraea coccinea* on a rocky reef in the shallow subtidal at Ilha Grande, Brazil and B) *Tubastraea* sp. on the gas production platform Peroá (PPER) on the Abrolhos Bank, Espírito Santo, Brazil. Photographs by Joel Creed (A) and Leonardo Bueno (B, used with permission).

Caribbean, Florida and Gulf of Mexico (Fenner 2001; Fenner and Banks 2004; Sammarco et al. 2004).

Tubastraea spp. present high growth rates, an early reproductive maturity and produce a large number of larvae throughout their life cycle (Ayre and Resing 1986; Glynn et al. 2008; de Paula et al. 2014). These species affect the structure and function of the native communities (Lages et al. 2011). Both sun coral species produce chemicals such as alkaloids (Maia et al. 2014a, b) which have antifouling properties and are deterrent to predation by fish (Lages et al. 2010a, b) and invertebrates (Lages et al. 2010a, 2012; Santos et al. 2013); they also lack generalist predators within their invaded range (Moreira and Creed 2012). They use a suite of different reproductive strategies, which results in high fecundity and precocious reproduction (de Paula et al. 2014), contributing to their rapid establishment and range expansion.

With their expansion, the sun corals are causing serious ecological, economic and social impacts in Brazil. One major impact is the change in biodiversity as they have been proven to be harmful to native rocky shore and reef populations and communities (Creed 2006; Lages et al. 2011, 2012, 2015; Mantelatto et al. 2011; Mantelatto and Creed 2015; Miranda et al. 2016). They compete with and cause necrosis to native species (Creed 2006, de Paula 2007; Hennessey and Sammarco 2014; Precht et al. 2014; Miranda et al. 2016) and also grow among and over commercially exploited mussel beds and farms (Mantelatto and Creed 2015). Lages et al. (2011) estimated that with increased cover of the sun corals the native community structure and function is lost. Silva et al. (2014) demonstrated that after ten years in 60% of sites where the sun corals were occasional or rare they became abundant or dominated. They estimated an expansion rate of 2.1 $km.yr^{-1}$.

Brazil is signatory to the Convention on Biological Diversity, which states that consenting parties should prevent the introduction of alien species and control or eradicate those already present which threaten ecosystems, habitats or species (Brasil 1998). Brazil also has a National Strategy on Exotic Invasive Species which incorporates and details 15 guidelines and action steps for their implementation (CONABIO 2009). However, traditionally little has been done to stop, prevent, control and eradicate invasive marine species along the Brazilian coastline.

After years of research and no purposeful action to tackle the growing problem of the sun corals on the Brazilian coast, in 2006 a management initiative, lead by a non-government organization, involving academia, government agencies and volunteers, called the Sun Coral Project (Projeto Coral-Sol in Portuguese, hereafter PCS) was established. PCS was initiated as a proposal developed by the first scientists to study the biological invasion of *Tubastraea* spp. in Brazil. They recognised the need for action and prepared the proposal under the joint auspices of the State University of Rio de Janeiro and a non-governmental organization concerned with marine conservation, today the *Instituto Brasileiro de Biodiversidade*. The initial objectives, based on the research and observations which had been carried out to date were to restore and conserve the marine biodiversity of the affected areas, generate extra income for local communities, provide biological and ecological knowledge for conservation and management, develop additional innovative solutions which add value to the management of the invader, develop an environmental education program and contribute to policy and legislation regarding the prevention and management of the sun corals in Brazil.

In 2006 PCS was initially structured as a research and outreach project linked to the State University of Rio de Janeiro, organized with Academic and Research, Student and Community Coordinators. Initial funding was provided by the State Foundation for Research in Rio de Janeiro (FAPERJ), the National Council for Scientific and Technological Development (CNPq) and the University—traditional research funding sources. Due to its innovative proposal (of replacing illegal trade in native coral with a legal trade in invasive corals, removing them and creating extra income) PCS was one of ten winners of the 11th Banco Real Universidade Solidária Contest, providing funding which allowed the start of training of coral collectors and management actions. Further sponsorship by the Petrobras Environmental Program (2009–2012) allowed a restructuring of PCS into Training, Environmental Restoration, Extra income and sustainability, Communication, Monitoring and Research Programs, with Environmental Education as a cross programs theme. A hotline (canal@coralsol.org) was created to receive new records of the corals in Brazil, a task force was set up for first response management and training, a Visitor's Center for communication and as a field base and a National Sun Coral Records Database created to gather all the quantitative and qualitative information on distributional records, research, monitoring, environmental education and management actions. In 2013 PCS was once again restructured to include an ample R&D&I Network as well as Management and National Monitoring working groups.

The aim of the present study is to critically evaluate the PCS as an NIS management initiative through an analysis of the organization and the results of the first ten years of action.

Materials and methods

Research

We analysed the contribution of PCS to the scientific knowledge of the two *Tubastraea* species by carrying out a systematic search of the available literature. We searched the biological literature for basic and applied studies of the biology and ecology of the two species. Literature searches were conducted using ISI Web of Science and SciELO – Scientific Eletronic Library Online (http://www.scielo.org) on the following terms: *Tubastraea coccinea*; *Tubastraea tagusensis*; *Tubastrea coccinea*; *Tubastrea tagusensis*; *Tubastraea aurea*; *Tubastrea aurea*; coral-sol; to compile a list of publications. *Tubastraea* and *Tubastrea* are synonyms and both are used in the literature and *T. aurea* is an older synonym of *T. coccinea*. We only used publications in peer reviewed journals.

From these 90 records we excluded publications which were generic (i.e. did not deal with a specific aspect of one of the species, such as lists of fauna from different localities, reviews which mention the species, etc.) but retained studies which dealt with multiple species where results were presented in a species specific fashion (74 remained) (Supplementary material Table S1). Finally we supplemented the list with a further 10 relevant papers using the terms "*Tubastraea*" and "*Tubastrea*" in the Google Scholar search engine (included in Table S1). Studies were collected for analysis until 20 May 2016. We then categorised the studies by the studied species, region and whether they had been carried out by researchers from the PCS Network.

Monitoring

In 2000 researchers that would later have the initiative to form PCS started to use extensive semi-quantitative monitoring to detect regional-scale change in the distribution of the two invasive corals along the Brazilian coast. Initially monitoring was carried out at Ilha Grande Bay and expanded to the North São Paulo coast, Sepetiba Bay and the Lakes region as new reports appeared. At each pre-established site two snorkel divers swam in opposite directions parallel to the rocky shore, in five one-minute transects. In each transect the divers estimated the density of coverage of each species of *Tubastraea* by assigning a DAFOR scale (Kershaw 1985) and values for classes of relative abundance: Dominant = extremely obvious populations forming many essentially monospecific patches $1 m^2$ at least one depth level, with very frequent isolated colonies and/or smaller patches spread throughout the substratum; Abundant = frequently occurring essentially monospecific patches of 50–100 cm diameter, with frequent isolated colonies and/or small patches spread throughout the substratum; Frequent = isolated colonies and/or small patches observed to be spread constantly throughout the substratum, with occasional occurrence of patches 10–50 cm in diameter; Occasional = less than 10 colonies or small groups but more than 5 colonies per minute dive; Rare = between 1 and 5 colonies found during a 1 minute dive; Absent (Creed and Fleury 2011). These observations were transformed to a quantitative relative abundance index (RAI) by assigning a scale from 10 (dominant), 8 (Abundant), 6 (Frequent), 4 (Occasional), 2 (rare) to zero (absent); a mean of the total of ten transects is calculated (de Paula and Creed 2005; Silva et al. 2011, 2014). Distributional maps were prepared using traditional methods (Surfer 8 Golden Software) using subset of points (n=144) taken at Ilha Grande Bay (Rio de Janeiro State) which had been studied for the longest period, four times since 2000.

Since 2005 a second Community Monitoring protocol, developed to quantify change in population density of the invasive corals and change in the benthic community structure, has also been used. Sites were set up in three distinct regions (one in north coast of São Paulo (Ilhabela), and two in the Ilha Grande Bay (Ilha Grande and the Tamoios Ecological Station Marine Protected Area). In each region eight sites were initially selected based on extensive monitoring data that represented the range of occurrence of *Tubastraea*: two absent sites; two sites with low relative abundance; two sites with medium relative abundance; two sites with high relative abundance (de Paula and Creed 2005; Lages et al. 2011). This was achieved by using SCUBA to place $0.25 m^2$ quadrats onto permanently marked 50 m transects placed at each site parallel to the coast in 1–3 m depth. Fifteen fixed position (initially randomized) and 15 randomly positioned (each time) quadrats were placed onto each transect. In each quadrat, divers estimated the cover of the major space occupying taxon or functional form (Steneck and Dethier 1994) in each of 25 (10 × 10 cm) subquadrats. The density of the two NIS was also estimated by counting individuals (colonies) in each quadrat. In the current study we compared the mean cover of the main benthic space occupying groups over two years (2005–2006) at one invaded site (Macacos Island, Ilha Grande Bay) as well as the average density of the *Tubastraea* spp.

Management

Since 2006 PCS has carried out different management actions where the sun corals have been detected

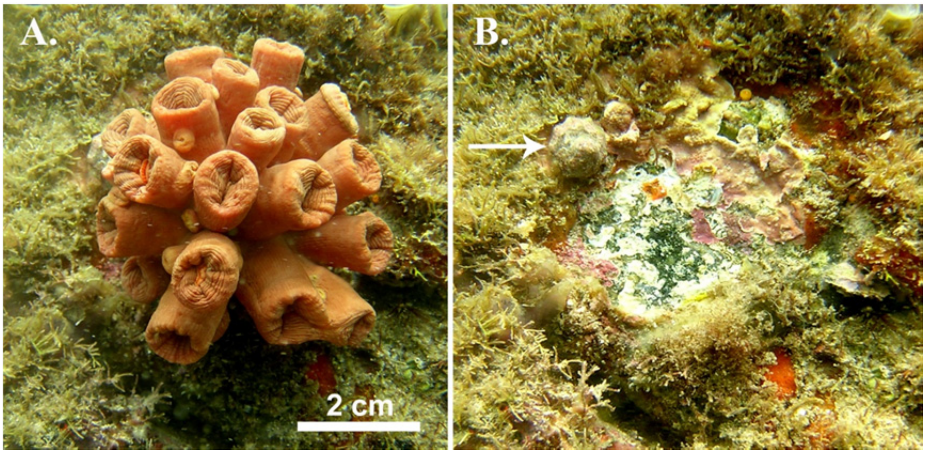

Figure 2. A) Before and B) after manual removal of a 3-4 year old colony of the sun coral *T. tagusensis*. Arrowed is a small gastropod not affected by the removal. Photographs by Joel Creed.

along the Brazilian coast. These actions include eradication of smaller populations in recently invaded sites and control measures to slow the spread and reduce propagule pressure so as to prioritize the protection and recovery of sensitive areas such as marine protected areas. PCS trained a group for the management of the sun corals which consisted of stakeholders, local managers and interested scientists. All received theoretical and practical training by the technical team of the PCS.

The sun corals eradication or control is achieved by the physical removal of the invasive corals *Tubastraea* spp. performed by divers (through SCUBA or snorkeling) using procedures in manuals and protocols developed by PCS (resources available at https://www.facebook.com/projeto.coral.sol/). Divers use suitable clothing and gear to swim in the sea and follow the usual health and safety rules for diving. The invasive corals are removed with a chisel and a lump hammer (Figure 2). The chisel is positioned at the coral base, which is detached from the substrate by a hit with the lump hammer on the other end of the chisel. This precise procedure does not impact the local biota (Figure 2). The largest corals are easily removed and thus are most often collected and extracted from the sea, which is efficient since these have the greatest breeding potential. In the case of small individuals (< 1 cm) these are eliminated directly on site, crushed with the chisel. Removed corals are killed by immersion in fresh water for two hours (Moreira et al. 2014) or enclosed in bags (smothering method) for seven days (Mantelatto et al. 2015). Dead corals are then returned to the sea in order to feed the detritus food chain (returning materials and energy to the ecosystem) or the skeletons are used by PCS artisans to create “souvenirs”.

A field sheet is used in each management action onto which are logged: 1) GPS coordinates; 2) amount of corals removed by species (or mixed, when the two species colonies grow on one another intermingled); 3) number of participants; 4) time and date of the beginning and end of the action; 5) destination of removed corals; 6) removal method (snorkeling or SCUBA); 7) elimination method (fresh water or smothering) and 8) other observations. Subsequently, the data are included in the National Sun Coral Records Database, maintained by PCS. In the present study we analyze these data.

Extra income

In order to engage and train coral collectors, we selected the local coastal community of Abraão Village, Ilha Grande Bay, Rio de Janeiro state as the first group of sun coral collectors in Brazil. This site was chosen because: 1) there was a large amount of invasive corals near the village; 2) the greater affinity of the residents with the sea; 3) the facility to carry out the work; 4) the village is the main gateway for tourism destination on Ilha Grande Island, so most of the residents work in boating related nautical tourism, which is highly seasonal. Furthermore, as the majority of its activities and jobs are related to the sea, the local coastal community are those who mostly suffer consequences of environmental degradation and impacts from bioinvasion.

The sun coral collectors were trained through theoretical and practical training about the history of the invasion, their impact, marine biology and ecology, oceanography, snorkelling techniques, basic oceanography, first aid basics, as well how to safely recognise and remove the corals, in addition to learning how to quantify and treat them after removal.

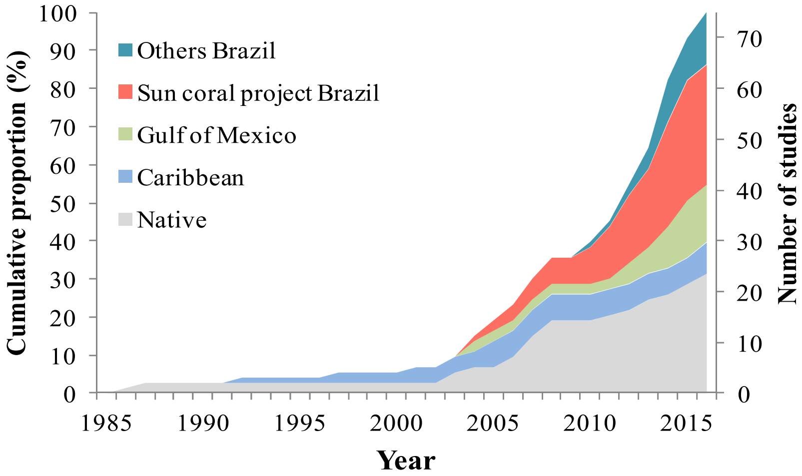

Figure 3. Number of studies and their proportion carried out by researchers involved in the sun coral project (PCS) and other researchers, by region, using data from an analysis of the literature available on *Tubastraea coccinea* and *T. tagusensis* Compiled from data in Table S1.

Collectors performed removals of the invasive corals near Abraão Village receiving an extra income to carry out such activities.

In order to investigate the socioeconomic impact of PCS on the participant coral collectors after engaging with the management of the sun-corals at Ilha Grande Bay, the PCS team conducted a questionnaire in 2012 in accordance with local ethics guidelines. Data on socioeconomic characteristics of interviewees, including, age, occupation, domicile, education, income, and also specific questions concerning their experience/knowledge, environmental concerns and behavioural change after engaging with PCS were registered from fourteen collectors.

Organization, environmental education, capacity building, training and communication

In order to investigate how PCS was planned and structured, the role of environmental education, activities of capacity building and training and communication, we compiled quantitative and qualitative information regarding structuring and activities from a database of internal reports, abstracts and other publications from the period 2006 to 2016. These data were synthesized in a descriptive and quantitative table (Supplementary material Table S2).

Results

Research

Scientific knowledge of the two species increased from 1986 to 2016 (Figure 3). SciELO provided no records not provided by the Web of Science while Google Scholar provided 10 references which Web of Science did not. Of the total of 74 relevant studies, 26 dealt with both species, 46 dealt exclusively with *T. coccinea* and two exclusively with *T. tagusensis* (Table S1). With regard to region, by 2016 there were more publications dealing with the species in Brazil (n=33, 45%) than in other regions around the world (Figure 3). The contribution to the knowledge produced by the PCS was 70% of all publications carried out in Brazil and was equal to the number of studies of the species carried out in the native regions (31.5%, n=23 publications each). Eleven publications were produced in the Gulf of Mexico (15%) and six (8%) in the Caribbean. No publications were found that dealt with *T. tagusensis* within its native range.

The studies published in journals by PCS were in a wide variety (18) mainly international peer reviewed journals dealing with biogeography, marine ecology and biology, oceanography, chemistry or biological invasion. This body of knowledge dealt with distribution (25% of studies), chemical ecology (14%), applied ecology (management), niche modelling and species associations (11% each), community ecology, growth and reproduction and ecological interactions (7% each) population ecology and taxonomy (4% each). These studies served as a nucleus for attracting further collaborative research projects and in 2013 an umbrella group, the Sun Coral R&D&I Network, was formed with 35 members from 14 different institutions with the remit to provide further knowledge and innovative science based solutions.

At the national level the PCS National Database compiled historical records and received new records of the sun corals in Brazil up to 2016 (Figure 4). These data demonstrate that the sun corals continued to expand their distribution along the Brazilian coastline from 2006–2016.

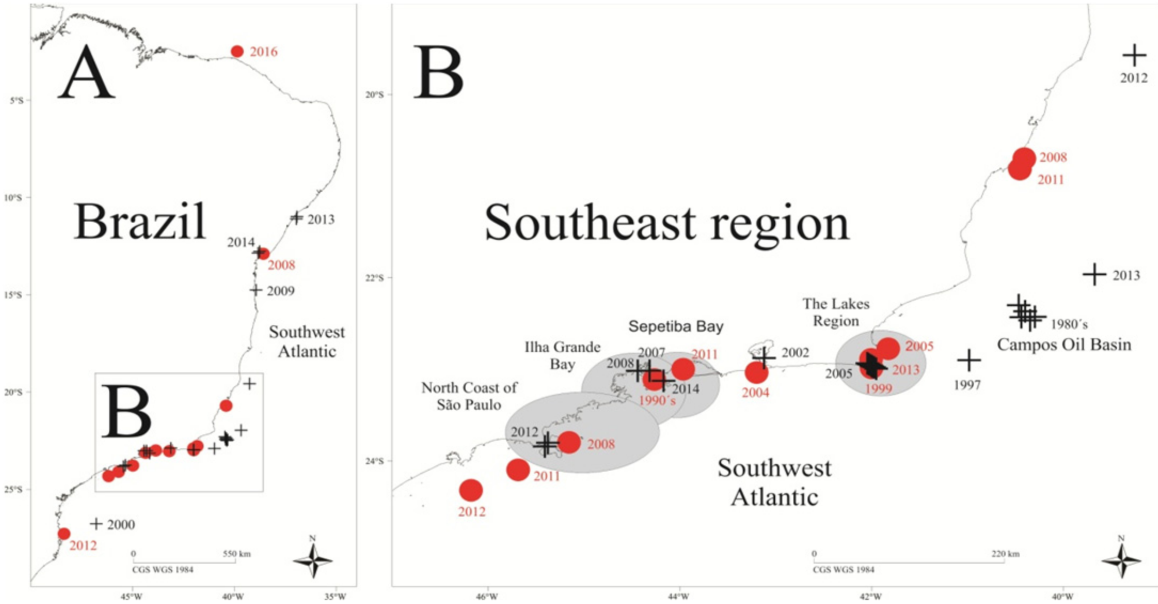

Figure 4. Map of new occurrences of the sun corals (*Tubastraea* spp.) on natural substrata and shipwrecks (circles) and on vectors (crosses - oil and gas platforms, drillships, monobuoys, riser support buoys, small pleasure craft) with year of record. A) Brazil and B) detail of the southeast region. Records were taken from the Sun Coral Project National Database, compiled in Table S3). Gray ellipses indicate regions where PCS carries out extensive monitoring.

Monitoring

The long-term monitoring of the PCS was able to map the distribution and follow the range expansion of the invasive sun corals at the regional scale in four regions on the Brazilian coast comprising 326 monitored sites (Figure 4; Table S3). For example, Figure 5 shows the expansion occurring from 2004 to 2011 of the two species of *Tubastraea* throughout the 144 monitored sites within the Ilha Grande Bay region (22º50′–23º20′S and 44º00′–44º45′W). Expansion was mainly into the central channel and into the west part of the Ilha Grande Bay.

Within one of the three regions monitored for community change, Macacos Island (23º04′36″S; 44º13′47″W) is a typical invaded site and between 2005 and 2006 the cover percentage and the density of the *Tubastraea* spp. increased at this site (Figure 6). Cover increased fourfold (0.8–4.1%) in a year while mean density increased threefold (from 45 to 150.9 colonies of *Tubastraea* spp.m^{-2}) over the same period (Figure 6).

Management

To the present PCS has removed over 232 thousand corals (~8.5 tons) through 165 actions in Brazil (Figure 7, Table 1). These were accomplished in part in conjunction with the various PCS partners, but mostly by the sun coral collectors at Ilha Grande Bay (see extra income, below). Management action started in 2006, but was quite irregular. Most actions were carried out in 2012 and no actions were carried out in 2010 and 2014. In general more *T. tagusensis* was removed (126,669 colonies) than *T. coccinea* (53,042 colonies), mixed colonies (41,996) or *Tubastraea* spp. (10,463, not identified to the species level) (Figure 7). PCS removed corals at 5 locations in four different states (Buzios and Ilha Grande Bay in Rio de Janeiro, Bahia, São Paulo and Santa Catarina) along the Brazilian coast (Figure 8a), though most actions were with collectors from the local coastal community of Abraão Village, Ilha Grande Bay (Figure 8b).

Extra income

Extra income has been achieved for 22 collectors and around 80 dependent family members. The sun coral collectors varied in age from 20 to 48 years old, half of the group have completed high school and the majority (86%) own their own residence. In Brazil the official minimum wage, a monthly value, ≈ US$170 in 2006 – US$250 in 2016. Before participating, 36% of coral collectors earned less than 2 minimum wages, 36% up to 4 minimum wages and 29% more than 6 minimum wages. However, 79% did not have a fixed job.

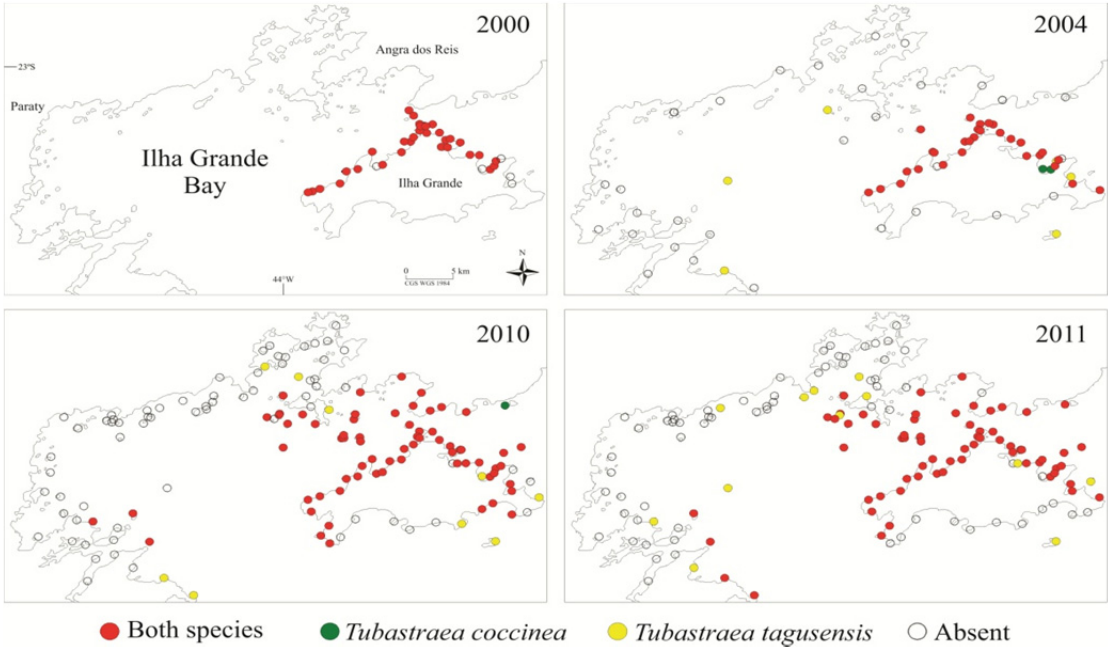

Figure 5. Maps of the range expansion of *Tubastraea coccinea* and *T. tagusensis* at 144 sites at Ilha Grande Bay over an eleven year (2000 to 2011) period as monitored by the DAFOR monitoring. In 2000 the two species were not treated separately.

Most coral collectors (86%) said their lives had improved in quality after they got involved with the PCS management activities. They stated that the extra income allowed them to purchase previously inaccessible goods such as microwave, mobile phone, computers, furniture and books. The majority of the interviewees also got more involved in environmental matters (93%). All of them acquired new knowledge and skills as they got involved with invasive species management. In their answers about what new knowledge they got while working with PCS, many of them identified information about invasive species and their real negative influence on native marine biodiversity, as well as about native biodiversity and the importance of a healthy environment. Another benefit identified by the interviews was that PCS encouraged organization and local leadership in the protection of the marine environment.

Environmental education, capacity building, training and communication

Supplementary material Table S2 presents the main environmental education, outreach, training, capacity building and communication actions of PCS. A total of 25 different types of actions were identified which were developed with varying frequency. This translated to a total of 289 actions directly affecting an estimated 143 thousand people. Most actions concerned communication and environmental education (Table S2).

Discussion

As an NIS management initiative, the first ten years of actions of the PCS have substantially advanced our knowledge of how to deal with marine invasive species in Brazil. The results presented here demonstrate that PCS has created a science-based, community supported, conservation initiative which provides information for government, the scientific community and stakeholders. Furthermore it has provided methods and human resources for monitoring and managing the sun corals invasion.

PCS is the first initiative to control invasive marine NIS in Brazil and the innovative proposal has directly benefitted society by taking advantage of the pest coral as a raw material. Coral skeletons are in demand throughout the world (Green and Shirley 1999; Rhyne et al. 2012) and are usually supplied by producing countries, which exploit their native species (Green and Shirley 1999; Roelofs 2008). PCS launched the proposal of commercially exploiting the sun corals as a sustainable way of carrying out control and generating extra income for local people most affected by the problem. PCS has become a national model for the control of invasive marine fouling species. It has also contributed to environmental education at all levels through communication of the theme.

In order to effectively manage a NIS it is necessary to know where it occurs, so mapping was a first priority of PCS. Monitoring range expansion was the next step as information on marine biological invasions, and how our actions are affecting desired outcomes, is only robust when based on appropriate monitoring programs (Ruiz and Crooks 2001; Wasson et al. 2002; Campbell et al. 2007; Crooks and Rilov 2009). The DAFOR method proved to be effective, rapid and low cost, suitable for the detection of range expansion and description of relative abundance over space and time at the regional scale. The long-term monitoring plan of PCS was able to map the distribution and track the geographic expansion of the invasion of *T. coccinea* and *T. tagusensis* at 326 sites on the Brazilian coast.

The coupling of regional monitoring with the National Records Database allowed a national picture to be drawn of the biological invasion of Brazil, pathways, the vectors responsible, as well as identify multiple introduction events and range expansion rates (reviewed by Creed et al., 2016). This large scale mapping was not only useful for identifying the risk of further introductions, but also for planning management actions and modelling future expansion or contraction scenarios at the regional and national scales (Riul et al. 2013; Carlos-Júnior 2015a, b).

The DAFOR method was certainly sensitive enough to detect change over time as range expansion occurred and communities shifted from invaded by a few individuals to being dominated by the sun corals. According to Silva et al. (2014) the method, although not designed as such, may also capture positive effects of management in some scenarios, as at one site, Macacos Island. There, the invasive corals have been sporadically manually removed from the rocky shores by trained divers from PCS's staff since 2006, and Silva et al. (2014) reported a reduction at this site. Furthermore, a shift away from dominance has been observed within the region.

Local monitoring, carried out in order to detect changes in the sun corals populations and quantify how they affect the natural benthic communities over time was also effective. Although extensive data on benthic communities' changes at sites is not presented in this manuscript, the method used by PCS has previously been critically reviewed by being compared to other available methods and has been considered to be the most cost-effective of those examined (Mantelatto et al. 2013). It has been shown to be sensitive in detecting change in number

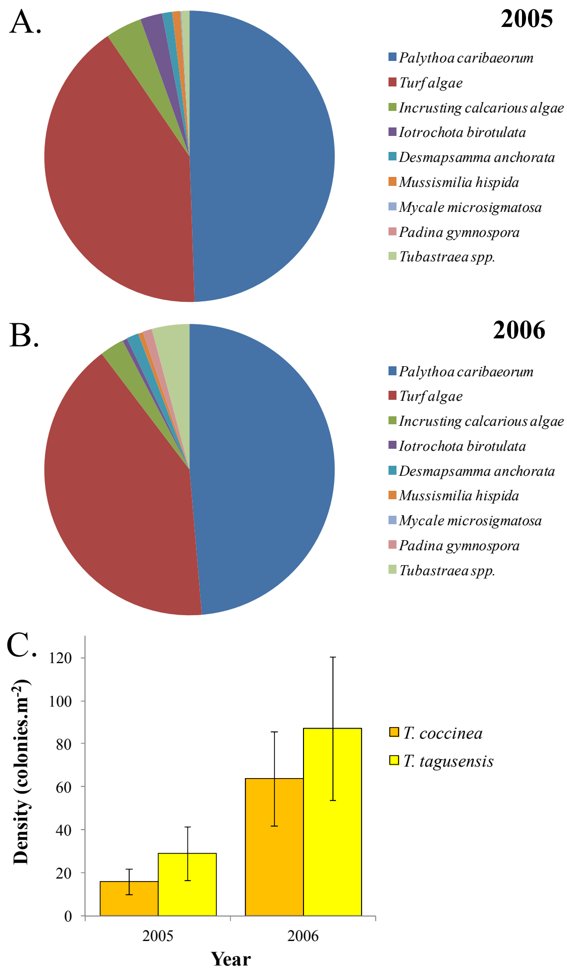

Figure 6. Abundance of *Tubastraea* spp. at a site (Macacos Island, (23°04′36″S; 44°13′47″W) undergoing intensive monitoring (Ilha Grande Bay region). Pie charts show cover (%) of the principal benthic space occupying organisms in A) 2005 and B) 2006; C) the mean colony density of each species (+ S.E.); $n = 15$

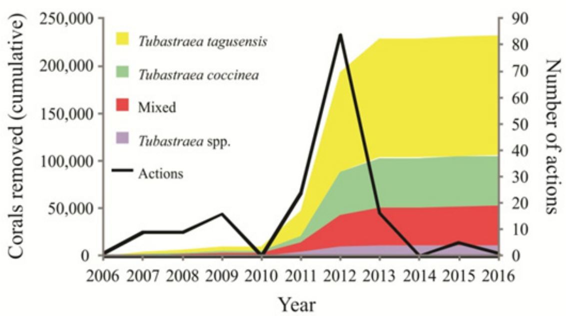

Figure 7. Total of *Tubastraea tagusensis*, *Tubastraea coccinea*, *Tubastraea* spp. (not identified to the species level) and mixed (when both species grow together) removed (cumulative) and actions (absolute n) by Sun Coral Project over ten years along the Brazilian coast.

Table 1. Sun Coral Project management actions and corals removed over the years. Tt = *Tubastraea tagusensis*; Tc = *Tubastraea coccinea*; M = mixed (when both species grow together) and Tni = *Tubastraea* spp. not identified to the species level.

Year	Actions	Corals removed (number of colonies)				
		Tt	Tc	M	Tni	Total
2006	1	6	35	54	0	95
2007	9	1,710	746	993	0	3,449
2008	9	1,223	659	550	0	2,432
2009	16	2,313	631	972	0	3,916
2010	0	0	0	0	0	0
2011	24	21,066	4,838	7,865	3,546	37,315
2012	84	77,890	38,884	22,391	6,182	145,347
2013	16	20,635	6,789	7,108	735	35,267
2014	0	0	0	0	0	0
2015	5	1,468	348	1,258	0	3,074
2016	1	358	112	805	0	1,275
Total	165	126,669	53,042	41,996	10,463	232,170

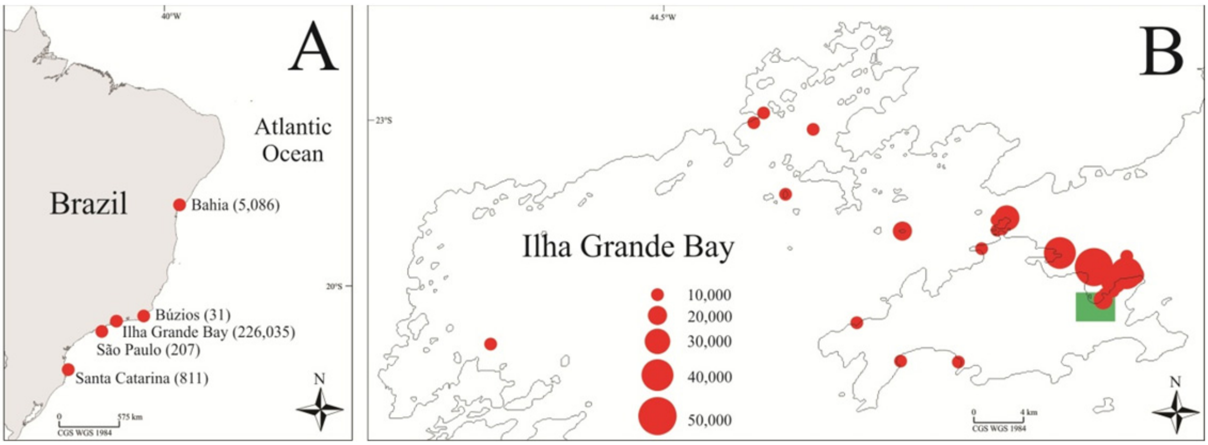

Figure 8. Sun Coral Project management sites: (A) on the Brazilian coast with the number of colonies of invasive corals removed per site and (B) detail of Ilha Grande Bay where the size of the circles represents the amount (colonies, n) of corals removed and the green rectangle Abraão Village.

and percent cover of coral colonies and efficient in describing change in benthic communities over time (Lages et al. 2011).

The regional mapping was coupled with information from the National Sun Coral Records Database gained through the report hotline as well as published and unpublished accounts. Engaging the public was extremely important in order to enhance a network of vigilance regarding the sun corals invasion in Brazil. We believe this to be especially important when considering the biological invasion of the marine realm from which we are necessarily removed, have minimal contact and limited opportunity to observe. Sport and professional divers and MPA managers were the groups most likely to report the sun corals to PCS and contrasted with researchers who were generally unwilling to report. The provision of anonymity was important when receiving reports of contaminated vectors, which attested that the public had confidence in PCS and desired action. It has been recognized that the way forward to dealing with marine biological invasions is to engage citizen scientists in detection and management efforts (Delaney et al. 2008), teach invasion science in formal classroom settings and train decision makers (Crooks and Rilov 2009), all of which PCS engaged in from 2006–2016.

Crooks and Rilov (2009) stated that whatever the role of the invasion biologist, communication is key. We identified that communication and public participation was of utmost importance in order to fulfil the aims of PCS. As well as the provision of new records, the environmental education, capacity building, training and communication provided an increased understanding of the problem of biological invasion. This, in turn, explained the desirability of eliminating the sun corals as a form of protecting native diversity, thus avoiding potential resistance by well-intentioned but misinformed local stakeholders regarding the removal of the invasive corals. Finally, it was possible to increase popular support for the control of the sun corals as stakeholders took on roles within the initiative as volunteers, coral collectors and agents of change. Meireles (2015) critically evaluated the environmental education actions of PCS. She identified that the actions of PCS allowed the empowerment of stakeholders and society, involved directly or indirectly with the problem, so they had sufficient information to participate in decision making and assist in the management of invasive species (Meireles 2015).

Effective marine biosecurity is the science based protection of native marine biodiversity and marine ecosystems through effective management and control of NIS (Hewitt et al. 2004, 2009). Our results identified 33 published studies concerning the sun corals produced in Brazil, showing that considerable knowledge exists that could be used to support management and control initiatives. Our results show that the first scientific studies of the sun corals in Brazil started approximately 20 years after the probable time of their introduction; the first monitoring action coincided which the first scientific studies in 2000.

A very large number of corals were removed by PCS but prior to its initiation the delay in management actions allowed the sun corals to spread. Management only began with the start of activities of the PCS, approximately 26 years after the invasion. The delay to act allowed for the rapid expansion (Ferreira 2003; Mantelatto et al. 2011; Sampaio et al. 2012) and growth of populations of the sun corals in Brazil. There is a consensus that it is desirable to act as soon as possible regarding the invasion of NIS, as success of eradication increases when the populations are small and restricted (Myers et al. 2000), so the lack of scientific knowledge should not be used as a reason to delay eradication or control programs (Shine et al. 2000). The knowledge needed to make a quick decision is usually minimal and intensive population biological research does not guarantee a solution to the problem of NIS (Simberloff 2003).

Total removal of sun corals without reappearance (eradication) has been carried out in isolated, accessible, recently detected populations at the range edge on several islands within the Tamoios Ecological Station MPA (Gomes et al. 2015) as well as an isolated population at the São Sebastião Channel, São Paulo state (Mantelatto 2012). Another focus is ongoing eradication programs in a number of Brazilian MPAs. The same methods are being used on reefs in the Flower Garden Banks National Marine Sanctuary, Florida, by National Oceanic and Atmospheric Administration of the United States (NOAA) (Precht et al. 2014).

The eradication of the invasive corals is now difficult in some localities, such as Ilha Grande Bay, Rio de Janeiro, but their control is imperative in order to decrease propagule pressure and to reduce spread. Most corals were removed by the sun coral collectors from the coastal community of Abraão Village between 2011 and 2013, when management actions had sponsorship. This contributed to local socio-economic development, while controlling populations of invasive corals. The community engagement in PCS improved their quality of life from different perspectives, including receipt of extra income and information. The receipt of extra income, improvement of quality of life, new knowledge and the right to participate was just, considering they are the main stakeholders impacted by the corals.

Most management effort by PCS has, however, been dedicated to slowing the spread of *Tubastraea* spp. and enhancing ecosystem recovery through control. The removal of the coral colony in itself may be considered a valid management action as it liberates space for native species, interrupts non-native-native interactions and eliminates the present and future production of propagules from that individual. Lages et al. (2011) demonstrated that when an invaded community reaches 45% cover of *Tubastraea* spp. it is effectively a different community, so uniqueness in community structure and ecosystem services are lost at that threshold. Despite this, initial management targets were set previous to Lages et al. (2011) and the number of corals removed rather than those that remained was monitored. Notwithstanding, early trials indicated that manual removal reduced mean cover from 41.6% to 2.1% (one month later); after one year, without further intervention, cover increased to 22.2%; with a second removal six months later mean cover was 5.7% after one year (de Paula 2007). It should be noted that these data are means, so mask the patchy nature of the spatial distribution of *Tubastraea* spp., which can vary from 0–90% cover at the 1m scale.

Continued efforts to eradicate or control marine species, coupled with clear and thorough reporting of both successes and failures in these efforts are still rare and urgently needed (Crooks and Rilov 2009; Ojaveer et al. 2015). PCS and their partners have carried out both successful eradication and control actions. Manual removal proved to be efficient in eliminating the invasive corals on rocky shores and coral reefs and is easy to apply without damaging native species. A wrapping method (Mantelatto et al. 2015) and others are being developed as an alternative for sites with very high cover or difficult accessibility.

Lessons learned and future directions

With regard to the sun corals incursion in Brazil it is important to point out that:

1. The framework for action that integrated research, monitoring, environmental education, management and public policy was essential to reach the PCSs objectives;
2. For control it is necessary to set clear management targets (Hewitt et al. 2009; Green et al. 2014) which should be based on three primary objectives 1) rapid response and eradication of new foci due to new incursions from vectors; 2) eradication of small isolated populations at the forefront of range expansion of known introductions (in order to slow the spread); 3) planned control actions within the invaded ranges to best use financial and human resources to reduce density (reducing propagule pressure and promoting ecosystem recovery);
3. Different monitoring protocols contemplating different spatial and temporal scales should be designed and used for 1) early detection (port surveys, etc.); 2) post incursion mapping; 3) quantifying negative change in benthic community structure and function as a result of invasion and positive change resulting from management programs;
4. New incursions will continue to occur and management actions will be less effective if the vectors are not dealt with by their owner/operators or governmental agencies (identified, cleaned and monitored);
5. The environmental agencies which are mandated to deal with invasive species in Brazil were at first insensitive to scientists warnings, unprepared and slow to recognise and respond to the sun corals problem. This was compounded by a lack of specific legislation and that a few scientists advocated a “do nothing, more research needed” approach. Consequently: 1) PCS needed to act independently as well as assume the responsibility of providing information so that those agencies recognised the problem and acted on it; 2) governmental agencies were slow to expedite and renew management licences legally required for PCS to act; 3) no funding was made available from environmental agencies so other sources needed to be found. These facts resulted in tardy incursion responses and discontinuity of management actions;
6. There was an overlap of jurisdiction between the Ministries of the Environment (fauna), and Fisheries and Aquiculture (fisheries resource) regarding the authorization for commercial exploitation. This resulted in a standoff regarding responsibility to authorise, expedite and renew licences legally required for the coral collectors to exploit the sun corals. In turn there was discontinuity in the provision of extra income and in the subsidisation of management costs through commerce, resulting in less effective management;
7. Although a body of research is not necessary to justify an incursion response, it was important to identify vectors and pathways of the invasion, provide governmental agencies with information for developing policy and develop a toolbox of methods for management;
8. Where eradication is possible it should be carried out; the exploitation and commercialization of the sun corals as a management strategy should only be encouraged in areas where the sun corals are well established and invasive; it should be carried out by trained persons and monitored by governmental agencies;
9. Environmental education and communication were effective ways of raising public awareness which resulted in: 1) stakeholders being informed of the problem, their responsibilities and opportunities; 2) the governmental agencies informed, motivated and/or pressured to act; 3) the detection and communication by the public of new incursion events;

Regarding the future there is a need to provide regular funding, continue developing new methods for management and rapidly expedite and simplifying licensing in order to encourage the model of extra income and its potential for becoming a popular occupation and thus a self-funding management strategy. Recently the Brazilian government has created a Working Group organized by the Ministry of Environment to provide technical advice in order to develop an upcoming National Sun Coral Control and Monitoring Plan.

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Supplementary material

The following supplementary material is available for this article:

Table S1. Results of a literature search for journal articles about *Tubastraea* spp.

Table S2. Actions carried out by the Sun Coral Project 2005–2016, principal programs attended (environmental education, capacity building, training, capacity building and/or communication), specific aims and quantity.

Table S3. *Tubastraea* spp. occurrences in Brazil: location name, coordinates (decimal latitude and longitude), first occurrence (year), type of substrate and reference.

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