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Review

Conservation of Brazilian coral reefs in the Southwest Atlantic Ocean: a change of approach

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ABSTRACT. Brazil has the most extensive and richest areas of coral reefs in the South Atlantic Ocean, with its fauna characterized by high endemism and adaptations related to its growth and morphology, to its coral building fauna and to the depositional environment that differ from other coral reefs around the world. In spite of the effects from changes in the global environmental, the main stress factors for Brazilian reefs are local level threats, such as pollution and overfishing. The effects from these threats reduce biodiversity and result in decreasing stocks at different trophic levels. The trend that currently exists, regarding marine resource use, implies that reassessing the conservation strategies is urgently necessary if the degradation of these environments is to be reversed. It is necessary that the practices used in adjacent watersheds be improved, combined with actions to protect and recover native vegetation, along with planning for developing coastal areas, which will ensure that sedimentation rates be controlled and pollution sources are drastically reduced. Brazil should have to adopt a multidisciplinary approach to lead an evolution from traditional threat management in individual portions of ecosystems to large-scale management strategies in complex socio-economic and natural systems.

Keywords: management, resilience, ecosystem services, stressors, adaptive management, Brazil.

INTRODUCTION

Coastal areas have been severely affected by a wide range of human activities over the past few years, and traditional resource management has failed to prevent habitats from being overexploited and degraded (Bellwood *et al*., 2004; Halpern *et al.,* 2008; Mora, 2014). Unregulated tourism, overfishing, uncontrolled coastal development, introduction of species and climate change are among the main human actions that are putting pressure on these ecosystems (Wilkinson, 2008). Given the current global decline in biodiversity, it is urgently necessary that conservation strategies designed to develop initiatives aimed at reversing the course of ecological degradation in the oceans be reevaluated (Fraschetti *et al.,* 2011).

The importance of healthy coral reefs is widely recognized; this importance includes the aesthetic, cultural and biological contribution coral reefs provide, in addition to their economic value to fisheries and tourism (McCook *et al.,* 2010). However, coral reefs continue to suffer from increasing human pressure in almost all areas of the world. There are pressures that act on the "local scale" that directly affect the surrounding populations and are caused by local phenomena (*e.g*., overfishing, destructive fishing practices and point source pollution). Despite having a localized impact, these pressures are present everywhere, and only rare and remote coral reefs are spared of their impacts (Wilkinson, 2008). However, these problems have local sources and effects, which makes coordinated preservation activities that can produce satisfactory results through local regulatory measures possible (D'Angelo & Wiedenmann, 2014; Rinkevich, 2014; Risk, 2014). In addition to these pressures, the so-called "global-scale pressures" (*e.g*., warming and acidification of the oceans) act synergistically with the local pressures, thereby intensifying their effects (McClanahan *et al.,* 2014; Mumby *et al.,* 2014).

The global reef crisis has mobilized a large number of authorities and scientists in an attempt to better unders-

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understand the workings of this complex system. Nevertheless, the main causative agents of the decline in coral reefs remain active and are globally distributed (De'ath *et al.*, 2012). Therefore, only with great effort, good planning and significant participation by society will a significant improvement in the management of coral reefs be achieved (Sale, 2014). The main threats to the coral reefs in the South Atlantic Ocean are presented in this study. The tools and management strategies that can be applied to reduce the impacts of these threats are also highlighted, while taking into account the existing regional particularities of the Brazilian coastline.

Goods and services from coral reefs

Ecosystem services can generally be classified into the following categories: service provision (*e.g*., fishing and pharmaceutical products obtained from marine organisms), regulation (*e.g*., water quality maintenance through the filtering effect of mangroves and seagrasses), culture (*e.g*., coastal tourism, recreation, exploration, recreational diving) and support (*e.g*., mangroves that act as nurseries for juvenile fish) (Levy *et al.*, 2005). Maintaining these services depends on complex interactions in the seascape as a whole (*e.g*., mangroves, seagrasses banks, coral reefs and the open ocean). This mosaic of environments provides grounds for spawning, nurseries, breeding and reproduction for a wide range of organisms, which act as a genetic reserve for future generations (Moberg & Folke, 1999).

Despite the recognized importance of the goods and services that reef environments provide, until recently it was common for their resources to be exploited in a harmful way (*e.g*., using coral for building material; producing cement and lime; applying coral in agriculture as a fertilizer and/or for correcting soil acidity) (Moberg & Folke, 1999). In addition, unregulated tourism (Smallwood *et al.*, 2011), overfishing (Johannes & Ripen, 1996) and uncontrolled coastal development (De'ath & Fabricius, 2010) conflict with all uses of ecological goods and services that are provided by this ecosystem.

Coral reefs in the Southwest Atlantic Ocean

Particularities of Brazilian reefs

Brazil has the largest areas of coral reefs in the Southwest Atlantic Ocean (Castro, 1994; Leão, 1994, 1996). These reefs are located outside the Caribbean hurricane belt, on a stable continental shelf, and are not subject to natural catastrophic events such as those observed in the Indo-Pacific and Caribbean coral reefs. Brazil's reefs have unique characteristics related to their growth and morphology, to the coral building fauna and to the depositional environment (Leão *et al.*, 2003). These reefs are found along Brazil's entire northeast coast (Fig. 1), from the state of Maranhão (0°53'S, 44°16'W) down to the north coast of the state of Espírito Santo (19°40'S, 39°17'W); reefs are also found on nearby oceanic islands such Atol das Rocas and Fernando de Noronha (Castro & Pires, 2001; Mazzei *et al.*, 2017).

Brazilian reefs are fairly heterogeneous. On the North Coast, there are oceanic communities that are dominated by coralline algae, with *Siderastrea stellata* being the main coral builder. The Northeast Coast has long lines of reefs along its fringe (coralline communities growing on the sandstone reefs), with parallel lines on the outer portion. The reefs on the East Coast occur in various forms; however, this region is characterized by the presence of endemic species of coral (*Mussismilia braziliensis*) and by the presence of "chapeirões" (mushroom-shaped coral formations) as important reef structures (Castro & Pires, 2001). These structures are formed by columns of isolated reef that develop near the surface and begin to expand laterally, thereby creating a complex reef structure that is different from the classic barrier reef structure (Leão *et al.*, 2003). This type of reef structure, which is typical for Brazil's East Coast, is not commonly found in other parts of the world.

Brazil hosts a small number of shallow-water scleractinian coral species, with 18 to 21 species (Laborel, 1970; Castro, 1994; Neves *et al*., 2006, 2008, 2010; Neves & Johnsson, 2009) distributed among 12 genera and nine families. However, these species are characterized by high endemism (≈50%) and by the presence of building species that date back to the Tertiary period (Leão & Kikuchi, 2005).

In contrast to most of the world's coral reefs, Brazilian coastal reefs are subject to high rates of siliciclastic sediment deposition, a result of river discharge and coastal erosion. During cold front periods, this sediment is re-suspended by the increased energy of waves, which increases the turbidity and alters the amount of light energy that reaches the coral (Segal *et al.*, 2008). The success of Brazilian coral under these conditions must be related to the fact that these resuspension events occur periodically, with corals growing in the interim periods. In addition, the prevalence of species with larger polyps and more effective mechanisms for removing sediment might reflect their ability to adapt to the high rates of turbidity in Brazilian waters.

Studies on the Brazilian reefs

The first scientific reports on Brazil's coral reefs date back to the 19th century and were the result of visits made by pioneering naturalists (Darwin, 1842; Hartt, 1870). Branner (1904) provided continuity to these early

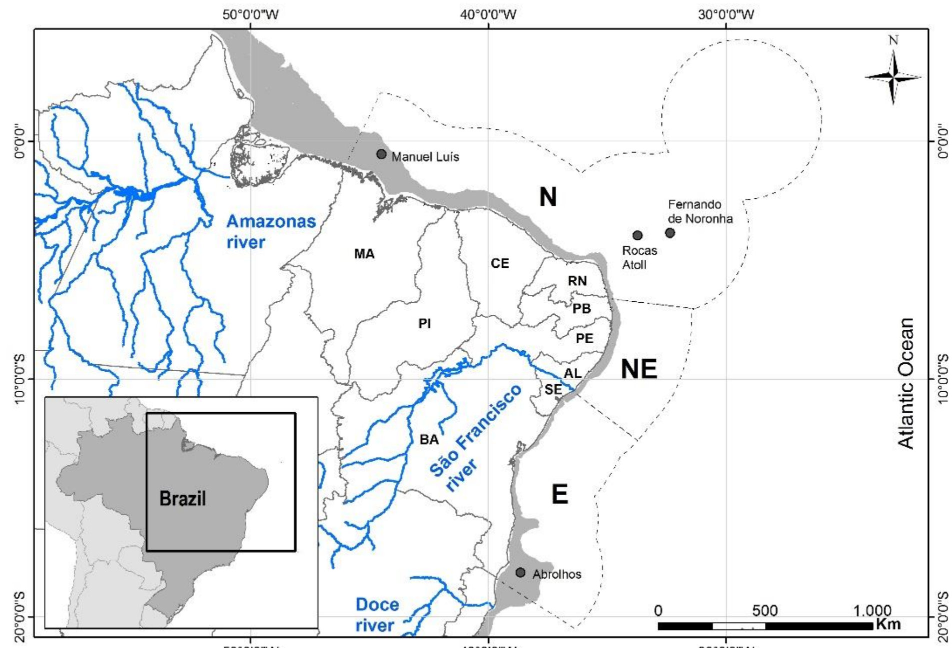

Figure 1. Map of areas in which coral reefs are found along the Brazilian coastline. North Coast (N), Northeast Coast (NE), East Coast (E). MA: Maranhão, PI: Piauí, CE: Ceará, RN: Rio Grande do Norte, PB: Paraíba, PE: Pernambuco, AL: Alagoas, SE: Sergipe, BA: Bahia. The dotted area represents Brazil's Exclusive Economic Zone (EEZ).

studies by producing a detailed description of the sandstone banks on Brazil's northeastern coast. However, the first study to comprehensively cover the subject was performed in the 1960s by French marine biologist Jacques Laborel. This study provided a qualitative and semi-quantitative description of Brazil's coral reefs located along much of its Northeast Coast, which is an important reference source for current studies (Laborel, 1970).

Marking the start of a new phase of knowledge gathering, several studies have provided information regarding the composition and distribution of important Brazilian reef formations (Leão, 1978; Petuch, 1979; Rios & Barcellos, 1980). The first National Marine Park of Brazil, Parna dos Abrolhos, was established in 1983 (East Coast, Bahia) (BRASIL, 1983) in light of the warning given regarding the need to protect and conserve reef systems.

Over the past 15 years, broad and varied research efforts have been undertaken to gain a better understanding of the way coral reefs work, including their peculiarities and processes. This effort began with a more comprehensive description of reef formations (Castro & Pires, 2001), starting with a string of studies ranging from an analysis of the main threat vectors, such as unregulated tourism (Ilarri *et al*., 2008; Sarmento & Santos, 2012; Albuquerque *et al*., 2015), overfishing and destructive fishing methods (Floeter *et al*., 2006; Francini-Filho & Moura, 2008a; Batista *et al*., 2014), coastal pollution and sedimentation (Costa Jr. *et al.*, 2008; Segal *et al.*, 2008; Silva *et al.*, 2013), introduction of species (Creed, 2006; Luiz *et al.*, 2013; Costa *et al.*, 2014) and climate change (Leão *et al.*, 2010; Santos *et al.*, 2014), to studies focusing on planning for conservation (Moura *et al*., 2013; Loiola *et al*., 2014; Santos & Schiavetti, 2014; Vilar *et al*., 2015) and new habitats (Amado-Filho *et al.*, 2012; Bastos *et al*., 2013).

Despite the unprecedented number of studies on Brazilian reef systems, information from these is rarely used in practical decision making or included in implementing actions designed to ensure the resilience of these systems and protect them from these threats.

Dangers to coral reefs

Growing human population

Humans who live near coral reefs and actively interfere with ecological processes are an integral part of this ecosystem (Cinner, 2014; Stevenson & Tissot, 2014). Approximately more than half the world's population (slightly more than 3.5 billion people) live up to 200 km from the coast (UN Oceans, 2013). In Brazil, 50.7 million of inhabitants (26.6%) live in coastal areas, mostly because of historical factors related to the occupation of the territory (IBGE, 2011). A portion of this population is directly or indirectly engaged in activities related to tourism, fishing, oil and natural gas production, as well as services that meet the economic dynamic of the local area and its surroundings.

Many reef scientists assume that local factors predominate and that isolated reefs are generally healthier and more resilient. However, in so many cases coral reef degradation is not correlated with human population density (Bruno & Valdivia, 2016). These suggest that local factors such as fishing and pollution are having minimal effects or that their impacts are masked by global drivers such as ocean warming.

In Brazil, most of the pressure placed on reefs is related to the lack of any regulation regarding the use of natural resources and to uncontrolled coastal development. The increasing human population and the subsequent demand for products and services have intensified the effects of threats to coral reefs. The following section will address the main coral reef threat vectors and their relationship with the growing human population that surrounds reef areas through an ecosystem approach.

Unregulated tourism

Among the main reasons why tourists are attracted to Brazil is the country's coastal regions, which constitute an important development alternative (MTur, 2010). However, the presence of a large number of tourists can be harmful, with the exception of a few locations that progressively regulate the regions and have the appropriate infrastructure to do so (Wilkinson, 2008). Globally, unregulated tourism is considered a cause of declining coral coverage, increased sedimentation, changes in local community structures, coral fragmentation, reduced coral growth and reproduction rates (*e.g.*, Hawaii (Hawkins & Roberts, 1993; Rodgers & Cox, 2003); Australia (Kay & Liddle, 1989); Egypt (Leujak & Ormond, 2008a, 2008b)).

More detailed studies regarding the effects of tourism on Brazilian reefs remain scarce. Marine scuba diving, which is often marketed for its environmental and educational value, has inflicted additional damage to coral reefs around the world (Hawkins & Roberts, 1993; Davenport & Davenport, 2006). Spanó *et al*. (2008) reported finding an elevated number of divers in the Abrolhos Marine National Park (East Coast, Bahia). The area is frequently affected by vessels and divers, who can directly interact with the environment, thereby breaking coral colonies and damaging the local reef system. High levels of scuba diving activity may cause changes in the structure of fish schools, short-term behavioral changes and a decrease in the richness and abundance of various species (Albuquerque *et al.*, 2015). However, measures to intensify supervision in Marine Protected Areas (MPAs), to define the local load capacity and to limit the daily number of divers, in addition to promoting visitor awareness, can mitigate the impact of tourism on Brazilian reef environments (Giglio *et al.*, 2015).

While evaluating the ichthyologic community of the Picãozinho reef (Northeast Coast, Paraíba), Ilarri *et al*. (2008) observed a sharp change in the structure and behavior of the local fish community as a consequence of unregulated tourism and supplementary feeding by visitors. One study on the human presence in the Porto de Galinhas reef (Northeast Coast, Pernambuco) found that marine trampling had led to severe changes on the meiofauna. The total density and the most frequent group were negatively affected, indicating that the loss of little known species is one of the potential consequences of human trampling of coral reefs (Sarmento & Santos, 2012). This current situation highlights the urgent need for the integration of scientific research and specific technical initiatives to help marine managers more efficiently allocate their resources.

Fishing activity

Artisanal fishing plays a key role in the local economy for many different countries; however, its impact on coral reefs can be catastrophic and may also have a significant effect on the community structure (Bender *et al.*, 2014; McClanahan *et al.*, 2014). Despite several successful examples of fishery management, most of the planet's fish stocks are currently being overexploited, and many are on their way to collapse (FAO, 2014).

Among the most prominent effects of overfishing are the general decline in abundance and biomass (Ruttenberg, 2001) and the reduction in the number of certain functional groups, such as piscivorous fish (De Boer *et al.*, 2001; Miller *et al.*, 2007), demersal fish that are associated with coral reefs (Tsehaye *et al.*, 2007), and herbivorous fish (Ruttenberg, 2001). Twenty-tree percent of all Brazilian marine fish stocks are estimated to be fully exploited and 33% overexploited (Bender *et al.*, 2014), which includes species of lower trophic levels (Pauly *et al*., 1998; Ferreira & Gonçalves, 1999; Freire & Pauly, 2010). Overfishing has altered the density and size structure of the top predators that live in Brazil's coral reefs (Floeter *et al*., 2006; Freire & Pauly, 2010), which has elevated the reefs' threat status (Bender *et al.*, 2013a, 2013b). Critical functional groups act to maintain the strength and resiliency of coral reef ecosystems, and their removal can have profound effects on the community structure and dynamics of these ecosystems (Mumby *et al.*, 2006; Hughes *et al.*, 2007; Crowder *et al.*, 2008).

Fishing resources are often managed through business sector regulation or institutional arrangements. These strategies include a wide range of rules, laws, economic instruments and community-based management (Abdullah *et al.,* 1998; Wiber *et al.,* 2004), with the objective of ensuring efficient and fair exploitation among stakeholders. Management regulations may include spatial and temporal controls of each catch or nominal fishing effort, which is usually supplemented with technical measures, such as restrictions on fishing equipment or size limits (Holland, 2003; Nobre & Schiavetti, 2013). In recent years, the need for holistic approaches (*e.g.*, Ecosystem-based management) to assess the impact of fishing on resources and ecosystems has been increasingly recognized (Crowder *et al.,* 2008).

Establishing exclusion areas that prohibit reef environments from being used ("no take areas") can promote the recovery of overexploited populations within their borders (Halpern *et al.,* 2010) and also provide a spillover of fish to adjacent areas for capture. During a study in the Corumbau Marine Extractive Reserve (East Coast, Bahia), Francini-Filho & Moura (2008b) recorded the biomass accumulation of commercially important species, which were found within the confines of an closed area and in open adjacent areas (0-100 m). Using a broader approach, by measuring different components of the reef ecosystem in the Abrolhos Archipelago (East Coast, Bahia), Bruce *et al*. (2012) found that protected coral reefs possess greater microbial diversity than more degraded reefs. Overexploited reefs in the Caribbean showed the growth of sponges (*i.e.*, boring sponges) on reef builders to be three times greater than in locations where there is less fishing (Loh *et al.,* 2015).

Fishing management and habitat protection can provide significant benefits, both by increasing productivity through greater growth or lower natural mortality of commercial stocks, and by protecting non-commercial species (Holland, 2003). Therefore, ensuring that ecosystems function normally, such that their services can be maintained, implies the need for governance models that are able to adaptively manage complex socio-ecological systems (Batista *et al.,* 2014).

Coastal pollution

Water quality has declined rapidly in areas lacking land use regulation, particularly in agricultural and developing coastal areas (Hertler *et al.,* 2009). However, in recent years, greater attention has been given to the effects of economic activities that are related to the use and occupation of land in the functioning of coral reefs (Fabricius, 2005; De'ath & Fabricius, 2010).

Coastal nutrient loading, sedimentation and introducing terrestrial organisms into the marine environment are among the main local factors linked to the recent global-scale proliferation of coral diseases (Harvell *et al.,* 2002; Selig *et al.,* 2006; Vega-Thurber *et al.,* 2014). In addition, increased concentrations of nutrients can cause an imbalance in the relationship between zooxanthellae (endosymbiotic dinoflagellates - *Symbiodinium* spp.) and the coral host (Hoegh-Guldberg & Smith, 1989; Koop *et al.*, 2001), which has important implications for the physiological yield of coral.

In Brazil, the reefs near the shore are subject to heavy discharges of siliciclastic sediments and receive significant volumes of nutrients from terrigenous sources, including nutrients from runoff, river discharge and groundwater input (Costa Jr. *et al.,* 2008). The potential for contamination by nutrients in waters off the Brazilian coast is critical, especially in waters near urban areas. Sewage collection and treatment are often inadequate or non-existent, with almost half of Brazil's cities (48%) not offering any type of service and only 28.5% treating their wastewater (IBGE, 2010).

According to Costa Jr. *et al.* (2008), there is a strong relationship between high rainfall and coastal productivity rates in the coral reefs on the East Coast (Bahia). This relationship suggests that soil drainage and groundwater infiltration are important factors regarding the input of nutrients along the coast. Nutrient concentrations also decrease with increasing distance from the coast, indicating an effect of nutrients from terrestrial and coastal sources, both natural (*e.g.*, mangroves, rivers) and anthropogenic (*e.g.*, infiltration of sewage, agricultural effluents). In addition, the widespread use of tanks in urban centers along the Brazilian coast further increases the concentration of nutrients from groundwater by the infiltration process (Leão & Kikuchi, 2005; Costa Jr. *et al.*, 2008). Enriching nutrient levels, as a result of groundwater contamination by domestic sewage on the East Coast (Bahia), may favor macroborer activity (*e.g.*, sponges and bivalves) at levels that are considered to be harmful to reefs (Reis & Leão, 2000). Bioerosion is encouraged when there is an increase in available nutrients (Hallock, 1988) in coral reefs, which can cause coral reef dissolution and degradation, as well as the destruction of coral colonies, which quickly lose their stability and become more susceptible to mechanical malfunctions (Leão & Kikuchi, 2005).

In Brazil, the amount of sediment flowing into the sea has increased significantly because of increased erosion of coastal areas. This erosion has been caused by the destruction of the Atlantic Forest by logging and the expansion of monocultures (Leão, 1994). The Northeast Coast features extensive sugar cane plantations located only a few kilometers from the shore, a region that hosts numerous coastal reefs. Industrial effluents, such as vinasse, which is a byproduct of the sugar manufacturing process, or waste from distillation following alcohol or sugar cane brandy production, have historically been dumped into the region's watercourses, causing damage to the marine environment. Hydrographic basin management is an essential component in multidisciplinary approaches to reef management (Ruckelshaus *et al.,* 2008).

Introduction of species

As globalization and international trade have increased, aquatic and terrestrial species have been deliberately or accidentally transferred to areas outside of their natural geographical distribution. For example, the exotic lionfish (*Pterois volitans*) from the Pacific was introduced into Caribbean reefs (León *et al.,* 2011; Hackerott *et al.,* 2013), and *Caulerpa taxifolia* algae have spread uncontrollably in the northern Mediterranean (Meinesz *et al.,* 2001).

According to Junqueira *et al.* (2009), ballast water and incrustation are the main man-made dispersion vectors of zoobenthos species in Brazil. In a recent study, Riul *et al*. (2013) demonstrated that two invasive species of the *Tubastraea* genus (*Tubastraea coccinea* and *Tubastrea tagusensis*) are able to find suitable habitats to thrive in along the Brazilian coast, which includes most of the national Marine Protected Areas (MPAs). These species are likely able to avoid native predators and cause changes in the settlement patterns of native colonizing organisms (Lages *et al.,* 2006, 2010), which radically changes the community structure of benthic environments (Carlos-Júnior *et al.,* 2015). Creed (2006) demonstrated the deleterious effect of *T. coccinea* on one of the main Brazilian coral-building species, the endemic *Mussismilia hispida.* Similarly, the exotic octocoral *Stereonephthya* aff. *curvata* has an allelopathic effect capable of causing necrosis in the tissues of the endemic gorgonian *Phyllogorgia dilatata*, which also has the capability to avoid predatory fish (Lages *et al.,* 2006). Exotic lionfish species (*Pterois volitans* and *P. miles*) are piscivorous predators that were introduced in the Northwest Atlantic approximately 15 years ago, which quickly spread and settled throughout the Caribbean. In Brazil, the first sighting of *P. volitans* was registered in May 2014 on the coast of the state of Rio de Janeiro; the species was possibly carried by natural larval dispersion from the Caribbean (Ferreira *et al.,* 2015). The possible ecological impacts of this invasion of native species are a legitimate cause for concern for the Brazilian government (Luiz *et al.,* 2013).

The extent and complexity of the effects of introducing exotic marine species have been increasingly recognized over the past two decades. Measures to prevent and control invading species represent a tremendous challenge for Brazil, which has a coastline that is approximately 8,000 km long. However, the government has undertaken considerable effort to implement systems to prevent and control invading marine species (Lopes *et al.,* 2009).

Climate change

Global warming and ocean acidification

Coral reef development has been slowed or even stopped several times during periods of climate change over evolutionary history, and its continuation shows that it has a remarkable resistance to these events (Pandolfi & Kiessling, 2014). However, the speed at which these changes appear to occur is increasing, and these changes have been charged with the loss of biodiversity and fishing resources in various coral reefs (Bellwood *et al.,* 2004).

Coral bleaching was a rare event before 1980, but since then it has increased in intensity and frequency (Glynn, 1993). Mass bleaching episodes have been attributed to thermal anomalies in the temperature of seawater and often occur during the period known as El Niño (Bruno *et al.,* 2001). Since 1998, thermal anomalies on the Brazilian coast have been monitored by satellite imagery, and studies have registered bleaching events that are associated with oceanic warming (Castro & Pires, 1999; Leão *et al*., 2010; Ferreira *et al*., 2012).

The known positive relationship between coral disease outbreaks and thermal stress resulting from climate change (Sutherland *et al.,* 2004; Selig *et al.,* 2006) have raised concerns regarding the consequences of declining coral reefs, because of the intensification of diseases (Leão *et al.,* 2010), especially because of reports of the sharp increase in the number of sites that have diseased corals (Francini-Filho *et al*., 2008). Having been isolated for millions of years, the Atlantic coral reefs should be particularly vulnerable to the impact of new diseases that are introduced (Wilkinson, 2004). There is no record of any disease virtually eliminating any marine species along the entire length of the Indian or Pacific Ocean, which is comparable to the disappearance of *Diadema* and *Acropora* in the Caribbean.

In Brazil, the increase on the incidence of coral diseases appears to be related to the synergistic effect of multiple stress factors (Francini-Filho *et al*., 2008).

Two positive sequential thermal anomalies (2009 and 2010) caused up to 50% of coral bleaching at the Fernando de Noronha Marine National Park and the Atol das Rocas Biological Reserve (North Coast, Oceanic Islands), with lower post-bleaching recovery and intensification of the disease outbreak (Ferreira *et al.*, 2012).

In 1998, sub-lethal effects on Brazilian corals were observed by Dutra *et al*. (2000) in the northern coast of Bahia (East Coast). Approximately 60% of the coral community was affected by bleaching; however, after one year, the coral had completely recovered. During the same period, approximately 16% of the world's reefs, particularly in the Pacific and Indian Oceans, were recorded as being lost, which was associated with the El Niño phenomenon (Wilkinson & Souter, 2008). During the 2010 El Niño event, at the Caramuanas Reef (East Coast, Bahia), endemic species of *Mussismilia* presented the lowest percentage of bleached coral colonies, and those that had undergone bleaching were completely recovered seven months later (Miranda *et al.*, 2013).

Ocean acidification is a primary concern for coral reefs because of its potential impact on the carbonate accretion rates of the main reef builders (Hoegh-Guldberg *et al*., 2007; Kleypas & Yates, 2009; Van Hooidonk *et al.*, 2014). Sarmento *et al*. (2015) performed a mesocosm experiment to investigate the effects of ocean acidification on the meiobenthic communities at the Marine Park Recife de Fora Municipal Marine Park (East Coast, Bahia). The results from this study indicate that ocean acidification causes important changes in the structure of marine benthic communities and can represent a serious threat to tropical reef food chains.

The effects of multiple stress factors can lead to a loss of resilience and an increased risk of regime change, which are often long-lasting and difficult to reverse (Hughes *et al*., 2003, 2005). These effects result in the homogenization of communities and ecosystems, which is caused by degradation in the complexity of trophic chains, in the diversity within functional groups and in the structure of biogenic habitats (Fraschetti *et al.*, 2011). Although the effects of climate change on marine ecosystems cannot be avoided by local management policies, improving environmental quality can have a strong positive effect on the strength and resilience of these systems. Greater investment in research and information integration can help managers make decisions that can mitigate the adverse effects of climate change on coral reefs.

The high endemism of Brazil's coral fauna, combined with the high turbidity of Brazil's water (Leão & Ginsburg, 1997) and highly abundant plankton when compared with the oligotrophic Caribbean and Indo-Pacific reefs, make Brazil's coastal coral reefs different from other coralline formations around the world. The corals in the turbid water of Australia rely more on heterotrophy than do corals from oligotrophic waters (Anthony, 2000), which may indicate that the former animals have adapted to a larger presence of prey or to lower light intensities in these environments. Thus, reefs in areas that are highly turbid, such as the Brazilian coast, may be more resistant to global climatic changes than those in clear water.

Regarding the reef communities along the Brazilian coast in particular, the following are some tools and management strategies that can significantly contribute to changing the current trajectory of coral reef degradation. These strategies must be based on a multidisciplinary approach that takes regional peculiarities into account, which is needed to protect the health of the ecosystems and provide people with the services that they require.

Instruments to maintain coral resilience

Ecosystem-Based Management as a change of perspective

Because of increasing evidence of the failure of traditional ways to manage resources with the objective of achieving sustainability and conservation, the need for management practices that view the ecosystem (in the marine context) as a whole is being increasingly recognized. Ecosystem-Based Management (EBM) has grown rapidly in recent years (Halpern *et al.*, 2010). EBM is regarded in many management discussions as a holistic way to manage an ecosystem and preserve its goods and services (*e.g*., McLeod & Leslie, 2009; Pollnac & Christie, 2009). The basic principle of EBM is based on an integrated and interdisciplinary approach that considers all sectors and aspects of an ecosystem, including those involving human beings. People are not only incorporated into the EBM in their roles as decision makers, opinion leaders and resource managers but they are also viewed as a key component of the ecosystem, with the products and services they provide and the changes to the ecosystems they cause through its use, and sometimes through their abuse of it (Shackeroff *et al.*, 2009). Implementing an EBM approach requires broad thinking in considering trophic chain interactions, connectivity, ecosystem function factors and how human activities interact with ecosystem species and services (Ruckelshaus *et al.*, 2008).

Currently, dozens of nations have embraced ecosystem-based management (UNEP, 2011). These nations aim to secure the marine management resources to protect the health of the ecosystem and provide necessary ecosystem services to the people. Australia's Great Barrier Reef (GBR) is the largest example of marine zoning in the world. The way that the GBR is handled explicitly emphasizes management at an ecosystemic level while also stressing conservation and rational use, public community participation and involvement, monitoring and performance evaluation (Dutra *et al.,* 2015). Summaries that justify the decisions made are based on a series of biophysical operational principles as well as their social, economic, cultural feasibility and management (Sheaves *et al.,* 2016). Management designed to promote resilience is explicitly mentioned in the documents, and soil-use management is therefore a critical component for successful reef management (Ruckelshaus *et al.*, 2008).

Despite success in other countries, EBM approach is poorly studied and rarely used in Brazil. However, Pereira *et al.* (2013) describes an assessment of the climate change vulnerability in the East Coast, which includes some of the most threatened tropical forests in the world which exist in juxtaposition to a rich and unusual coral reef. Forest and coral reefs provide important ecosystem services in this area, including fisheries, coastal protection, freshwater, prevention of sedimentation and crop pollination. Additionally, two potential adaptation interventions have been presented for potential implementation in Bahia State. One aims to protect coastal infrastructure and improve fisheries in the face of sea level rise and changes in wave dynamics by developing activities that promote more appropriate coastal planning and by protecting offshore coral reefs. The other aims to increase resilience and reduce vulnerability of people, ecosystems and ecosystems services by adding Ecosystem-based adaptation recommendations in a municipal plan of conservation and restoration of the Atlantic Forest.

Managing resilience and human uses with protected areas

Establishing protected areas is one of the most effective methods for conserving biodiversity by maintaining viable populations of native species in their natural system (Game *et al.*, 2009). The number of Marine Protected Areas (MPAs) around the world is increasing. Currently, 2.3% of the Earth's oceans is under some form of protection, and 28 countries have more than 10% of their marine areas included within protected areas (Spalding *et al.,* 2013). However, only 0.91% of the Earth's open ocean regions is protected (Toropova *et al.,* 2010). During the 1990s, scientists, funding agencies and civil society organizations began promoting Networks of Marine Protected Areas (NMPAs) as a tool to help alleviate the fragmented and uncoordinated nature of approaches used for the protection of marine species and their habitats (Lubchenco *et al.*, 2003). Within their limits, effective networks of MPAs incorporate links between habitats that meet the biological requirements of various species throughout their life cycle, thereby increasing the resilience of systems against large-scale threats. MPAs are an important component of many EBM approaches; however, alone they do not meet all their management aspects (Halpern *et al.,* 2010).

Developing countries are permanently faced with a serious lack of resources, which limits the number, size and effectiveness of MPA networks; this limitation in turn increases the likelihood of MPA networks being referred to as "paper parks". Brazil has recently committed itself to achieving the Aichi Biodiversity Targets, where the objective is to cover 10% of its ocean and coastal areas within an effectively managed National System of Protected Marine Areas (SNAMP) that will be ecologically representative and well-connected up to 2020 (MMA, 2013). The construction and designation of the National System of Conservation Units (SNUC) and the National Protected Area Strategic Plan (PNAP) represent significant historical events that provide legal mechanisms for describing and implementing various categories of protected areas (BRASIL, 2002). Another important step is the Marine and Coastal Protected Areas Project (GEF Mar), which was initiated in 2014 (MMA, 2015a). This federal government initiative was created and implemented in partnership with private institutions and civil society, the purpose of which was to promote the conservation of marine and coastal biodiversity. The main objective of this initiative was to support the creation and implementation of a representative and effective system for Marine and Coastal Protected Areas (MCPAs) in Brazil to reduce the loss of marine and coastal biodiversity. This Project is aligned with Brazilian national policies for biodiversity conservation and the sustainable development of coastal and marine zones: National Biodiversity Policy; National Biodiversity Targets for 2010; National Policy for Marine Resources (PNRM), including the Sectorial Plan for the Sea Resources (PSRM VIII 2012-2015); National Coastal Management Plan (PNGC); and Evaluation, Monitoring, and Conservation of Marine Biodiversity (REVIMAR), among others.

One of the recurring themes in Brazil is the dilemma regarding the balance between creating more protected areas and efforts to implement the ones that already exist. Broad support from managers and Brazilian Government authorities in favor of the national policy to create more MPAs along the coast exist (Gerhardinger *et al.*, 2011), supported by the poor current biological representation and by the political contract that was entered into with the Convention on Biological Diversity (CBD). However, currently, there is not nearly enough protection for Brazilian marine environments, with only 1.5% of Brazil's marine areas being legally protected by sustainable use areas (1.4%) and no take areas (0.1%) (MMA, 2015b). This fact indicates that formal national marine resource management is in its early stages. The concentration of Conservation Units in coastal environment results in a low representation of marine ecosystems in the SNAMP (Schiavetti *et al.*, 2013). In addition, the rate at which MPAs have been created over the past 15 years has been low (20%).

The strategic expansion of MPAs in Brazil is urgently needed to cover large unprotected stretches and to achieve an ecologically functional and efficient MPA network (Floeter *et al.*, 2006; Magris *et al.*, 2013). Several areas earmarked as a high priority for protection in the Exclusive Economic Zone (EEZ) spatially overlap areas that are important for the conservation of endangered species and areas that have been a priority for larger taxonomic groups, such as coral reefs (Moura, 2000), marine bird species at a high risk of extinction (Machado *et al.*, 2013), and centers of endemism for reef fish in the Southwest Atlantic Ocean (Moura 2000; Floeter *et al.*, 2008; Vilar *et al.*, 2015). The lack of adequate planning on an appropriate spatial scale is evident; such planning involves different sectors of interest (Vila-Nova *et al.*, 2014) and aims to integrate MPAs and economic activities with high environmental impact potential (*e.g.*, fishing, mining, dredging and gas and oil exploitation) (Moura *et al.*, 2013).

Additional joint management tools are required, including those that address land and offshore areas within a given system. One of the fundamental principles of EBM is spatial integration, which brings together coastal resource management and marine area protection (Tallis *et al.*, 2010).

Cooperative management or co-management

Scientists and marine resource managers have recently begun to study the different aspects of cooperative management, or co-management, more deeply. The term refers to institutions that are involved in shared power and intense participatory decisions, which creates agreements between government(s) and marine resource users (Berkes, 2009). The emergence of these agreements is a result of perceived failures of government management systems (Jentoft, 1989). In the early 2000s, the Pew Oceans Commission (POC, 2003) and the US Commission on Ocean Policy (USCOP, 2004) indicated that marine resources should be managed through a global strategy for ecosystem-based management that considers factors that drive human behavior and their choices regarding the use of marine resources as well as their interactions with the areas. However, expanding EBM plans to oceans involves considering broader aspects such as trophic interactions, ecosystem function drivers and the interaction between human activities and ecosystem services, as well as the interaction with the species that are directly and indirectly affected by these activities (Ruckelshaus *et al.*, 2008).

In Brazil, the Costa dos Corais Environmental Protection Area (Northeast Coast) implemented a cooperative management initiative. This area is the largest federal marine Conservation Unit in Brazil in size and covers areas in the states of Pernambuco and Alagoas, spanning an area of over 400 h and approximately 120 km of beach. This area is a Sustainable Use Conservation Unit, a category that seeks to incorporate consistent environmental conservation goals and the direct (fishing) and indirect (tourism and research) uses of natural resources. The strategy of creating and strengthening the Municipal Councils for Environmental Defense (COMDEMA) was adopted in the Conservation Unit's surrounding cites. These councils are collective entities composed of representatives from government and civil society. These councils are in charge of deliberating, consulting, regulating and supervising local environmental issues as well as integrating the structure of local authorities into the National Environmental System (SISNAMA). These local collective boards are able to employ participatory and deliberative processes more efficiently, which enables greater decision-making swiftness than that exhibited by entities associated with federal institutions (Ferreira *et al.*, 2006).

Another important strategy that makes the reconciliation of different interests and the collective construction of solutions possible is the creation and implementation of Hydrographic Basin Committees. These committees are collective bodies that are part of the national system of National Water Resource Management and have existed in Brazil since 1988. The diversified and democratic composition of these Committees contributes to all sectors of society that have an interest in using water from the basin, and the Committees have representative and decision-making power over the management of water use. Among the main responsibilities of the Committees are the following: to approve the Water Resources Plans for the basin; to arbitrate conflicts over water use in the first administrative instance; and to establish mechanisms and make suggestions regarding the amounts to charge for water use.

Systems of governance must support the ownership and empowerment of users as administrators for the resilience of reefs while providing incentives for preventive protection of herbivorous stocks and implementing flexible restrictions (*e.g*., protecting endangered species) (Bellwood *et al.*, 2004; Stevenson & Tissot, 2014). Although there are still only a small number of examples of national participatory management, this approach represents a positive aspect of SNUC policy that allows for the active participation of social groups in the management of Sustainable Use Conservation Units. In addition, this aspect encompasses the concept of fairness that is present within Aichi Targets, which recognize the role of local communities in establishing and managing Protected Areas (Nobre & Schiavetti, 2013).

The role of science in coral reef management

Managers of reef environments will find their challenges increase with approximately half the world's population living in coastal areas in 2015 (UN-Oceans, 2013). This increase in population will put unsustainable pressure on coastal resources, including depleted fishing stocks in many poor countries. New efforts are focused on administrating local and regional anthropogenic pressures with the objective of strengthening reef resilience (Hughes *et al.,* 2010; Mumby *et al.,* 2014).

Regions such as the Caribbean, Southeast Asia and Eastern Africa have suffered great losses in coral coverage, whereas many reefs in remote regions where human pressures are still minor remain healthy. Some coral reefs that had previously been devastated by acute events (*e.g*., bleaching, hurricanes) have demonstrated good resilience, with a healthy and rapid recovery. On the other hand, the recovery of reefs that have been subjected to chronic threats such as domestic and industrial pollution, unregulated tourism, destructive fishing practices, habitat loss and uncontrolled coastal development has been slow or stagnant (Wilkinson, 2008).

It is considered essential that long-term data be acquired to understand environmental change and to support management actions and programs. In Brazil, an important event in this direction was the creation of the Long-Term Ecological Research Program (PELD) in 1997. The PELD plays a multifarious role in consolidating research in different ecosystems using a dynamic approach; organizing databases and establishing a scientific basis for evaluating impacts of human activities; and creating opportunities for qualified human resources training. In 2012, PELD research sites were created on the Abrolhos (East Coast) and Oceanic Islands, which are home to important coral reef formations. In addition, Brazil has implemented the National Program for Monitoring Coral Reefs (Reef Check Brazil) since 2002, which covers all the main coral reef areas in Brazil. Approximately three years ago, through the Brazilian National Research Network on Marine Biodiversity (SISBIOTA), an unprecedented effort was undertaken to conduct research on Brazilian marine biodiversity, which covered the entire coast in an integrated manner. Despite these advances, the real barriers to developing a solid program for generating knowledge on marine systems are the low volume of investment in research and the discontinuation of financing.

Some of the results of these initiatives are product innovation, public processes or policies (*e.g*., National Biodiversity Monitoring Strategy, Action Plans for Endangered Species), and the dissemination and transfer of knowledge. Brazil has a strong professional capacity, but it still suffers from serious political and financial constraints in implementing measures to conserve its natural resources. One recent example is Ordinance 445/2014 from the Brazilian Ministry of the Environment (MMA), which defined the Official National List of Species of Fish and Aquatic Invertebrates Threatened with Extinction (Lista Nacional Oficial de Espécies de Peixes e Invertebrados Aquáticos Ameaçados de Extinção). The list is the result of a careful study that spanned five years, involved more than 1,300 specialists and used the best available information. The official list of endangered species is an internationally recognized instrument and is provided for in the National Biodiversity Policy, in accordance with Decree No. 4,339, August 22nd, 2002 (Article 5). However, because of fears regarding economic losses, the fishing sector sought help from the Ministry of Fisheries and Aquaculture in an attempt to overturn the ordinance that established comprehensive protection for 475 endangered fish. Among the various reactions to this plea, the Ministry of the Environment has twice postponed enforcing the ordinance, in addition to extending the deadline and creating special rules for commercially valuable fish.

Most of the fisheries in Brazil are under no control or standardization. For those fisheries that are considered managed, the measures are restricted to minimum catch sizes or restrictions on fishing time and equipment, which are globally recognized as being insufficient to effectively manage and sustain fish stocks. In addition, the last statistical bulletin for Ministry of Fisheries and Aquaculture was published in 2012 (MPA, 2012). Since then, there have been no official consolidated data regarding Brazil's fishing activity. Situations such as this one reflect the historical fragility of natural resource management in Brazil. Today, Brazil must address enormous gaps in terms of monitoring, with the absence of an efficient and continuous system to collect and analyze technical and scientific data, which would make it possible to establish management measures and suitable development policies to maintain income from economic activity and to preserve social benefits, biodiversity and the health of the oceans over the long term.

Brazilian conservation dilemmas are interdependent and perceived at different levels and scales in the governing system. Not only are these dramas related to conflicts and financial constraints, but they also reflect the social, cultural, political and economic dynamics of modern Brazilian society. A lack of financial resources, a high level of bureaucracy, a lack of human and operational resources are also present in other public administration sectors, which reflects the cultural aspects and recent history of Brazilian democratic institutions (Gerhardinger *et al.*, 2011). This situation in turn implies that managing this natural system must transcend social boundaries, property systems, and political jurisdictions, and therefore management holds broader implications for human well-being and ecosystem governance (Duraiappah *et al.*, 2014).

CONCLUSIONS

Much effort is still required if Brazilian reefs are to be effectively conserved. Despite the creation of numerous protected areas, only one small area is fully protected with the rules completely enforced. To enable effective ecosystem management approaches, three linked and supporting concepts are necessary: corporate responsibility, social justice, and ethics (Bundy *et al*., 2009). There is an urgent need to encourage multidisciplinary research, with the goal of untangling the complex processes operating at different scales and, in the same framework, to explore the impact of global changes in time and space (Fraschetti *et al*., 2011). Is critical to view marine resources holistically since they are tied to terrestrial systems and span political and jurisdictional boundaries. Multidisciplinary consortia, involving both social and natural scientists, can prioritize and collect the necessary data for science-based EBM, the planning of which is ideally governed by robust scientific guidelines and undertaken by a diverse group of decision-makers, managers, stakeholders, and the general public (Claudet, 2011). Where they exist, MPAs should be viewed as a starting point for EBM.

The key to conserving coral reefs is to evaluate ecosystem goods and services, thereby demonstrating that coral reef conservation is in line with relevant social and economic benefits as well as cultural incentives and values (Stevenson & Tissot, 2014). Unless critical functional groups are actively managed to support reef resilience on a large scale, any small-scale success may be unable to stop the decline in reef systems as a whole. We need healthy reefs to have healthy people. This theme is useful for linking tourism, livelihoods, food and nutrition security and cultural and spiritual well-being, which ensures a conservation partnership among all interested parties (Duraiappah *et al.*, 2014). The time for Brazil to adopt a culture of ecosystem-based management is now. Brazil must use solid interdisciplinary science in conjunction with interested parties through an inclusive process that is proactive and responsible.

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