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Contents

The Network for Monitoring Coastal Benthic Habitats expresses its deepest sympathies and shares its memory of Prof. Valéria Gomes Veloso, Verônica Fonseca Genevois e Monica Dorigo Correia, who passed away during the early stages of ReBentos. We will greatly miss their spirit, creativity, and contagious positive energy. Their contributions to science, teaching and society will motivate future generations of marine scientists.

VALÉRIA GOMES VELOSO

Prof. Dra. A. Cecilia Z. Amaral
Universidade Estadual de Campinas

Dra. Elianne Pessoa Omena
Universidade Federal do Rio de Janeiro

In the book "Natural History Guide of Rio de Janeiro" published in 2012, Valeria Veloso, in describing the coast of Rio de Janeiro in a short introductory text, recorded her passion for the sea, particularly the beaches: "the landscape of Rio de Janeiro is marked, for everyone, not only by the profile of its mountains and the green slopes of Serra do Mar, but also by an indented coastline, composed of sandy beaches, rocky shores, bays and coves. The sea is part of the carioca's day-to-day, but the marine life diversity is unknown to most of its residents and visitors". Valeria had special interest on the life cycle of sandy beach invertebrate species, striving to establish links between knowledge built through years of research and environmental conservation practices. She faced major challenges when conducting research projects at UNIRIO, where she worked for over twenty years, with determination and optimism. Her joyful and positive spirit was relayed to her many students and trainees in her laboratory. Up to this day, she has been an inspiration to those who dedicate themselves to the study of sandy beaches and marine biology in Rio de Janeiro.

Born on December 15, 1961
Died October 18, 2013

VERÔNICA FONSECA GENEVOIS

Prof. Dr. Ricardo Coutinho
Instituto de Estudos do Mar Almirante Paulo Moreira

Veronica had a full life. She graduated in Natural History from Universidade Católica de Pernambuco, received her Masters in Zoology from the Universidade Federal do Parana and her doctorate from the Université de Nantes, in France, where she fell in love with meiofana. She did postdoctoral research at the Instituto de Estudos do Mar Almirante Paulo Moreira, in Arraial do Cabo, and at Ghent University in Belgium. As a researcher, she published 51 scientific papers. As a teacher, she was incomparable: she spoke about meiofauna with a passion so great that it was contagious. She trained 31 masters and twelve doctors. Many of the experts on these organisms in Brazil were either supervised by her or used Veronica as a primary reference. She fascinated others with her ability to encourage people and to understand the nature of a person from a single glance or gesture. Veronica was very sensitive and always showed herself completely. She was a talented belly dancer and spoke with emotion about this art. She had a great capacity to forgive people. She accepted her limitations and weaknesses, turning them into virtues. For her it was not necessary to hide insecurities, problems, or doubts. She knew how to say the right words at the right time. She knew to sensibly qualify the level of each problem, and always had a ready solution. Perceptive, she always followed her intuition when making decisions. Her existence brought light into the lives of everyone who knew her.

Born on July 09, 1951
Died December 02, 2013

MONICA DORIGO CORREIA

Prof. Dra. Hilda Helena Sovierzoski
Universidade Federal de Alagoas

Born in Rio de Janeiro, she loved salt water, just seeing the sea, admiring its immensity and nuanced color, swimming, diving... or doing those all together. Correct in her actions, she always strove to do everything in her life with excellence. She was passionate for Alagoas, her adoptive state, and prepared several of the next generation of biologists across Brazil and overseas. She studied biology at Universidade Santa Ursula, received her Master's degree from Universidade Federal do Paraná and her Doctorate from Universidade de São Paulo. She received Full Professorship at the Universidade Federal do Alagoas after an illustrious 24-year career at the institution. Involved with biodiversity projects, she directed a post-doctorate at the University of Central Florida, studying the molecular biology of marine invertebrates. She was active, vigorous and positive in her actions to defend the environment. She loved nature, advocating for it sometimes very frankly, contributing valuable arguments. She realized the need to better educate undergraduate and Masters students in order to continue the preservation of marine ecosystems. Her words, attitudes, thoughts and ideals will be remembered in her books and publications. Her work will continue to be followed by those who worked directly with her.

Born on December 15, 1962
Died May 25, 2016

Linking biodiversity and Global Environmental Changes in Brazilian coastal habitats

The Earth's climate is changing at a time when society is re-evaluating its relationship with nature and with the services that natural systems provide to human societies. Human actions, which are the major cause of these changes, also reduce the ability of ecological systems to cope with and adapt to the new scenarios. As a result, in the near future only the biota but humanity as a whole will feel the effects of our unsustainable way of life. Among the expected effects, there is the compromising of ecosystem services that are the basis of life and the human economy in diferente parts of the globe.

Oceans are central to the climate system, recycling half of the oxygen that we breathe and absorbing half of the carbon dioxide that we emit through the burning of fossil fuels. The oceans hold 97% of the Earth's water and 95% of all mobile carbon, providing food and livelihoods. Determining the effects of Global Environmental Changes (GECs) on the oceans are critical to understanding what is changing, how is it changing, and how these changes will influence society. Direct and indirect effects of GECs on the marine environment are already perceptible, but others can only be projected based on observations, experimentation and modeling efforts. We have only a rudimentary understanding of the sensitivity, vulnerability and adaptability of natural and managed marine ecosystems to GECs, especially in the South Atlantic.

On the Brazilian coast, the existing baseline, monitoring and predictive studies are insufficient to understand the detrimental effects of GECs. The lack of long-term studies of biodiversity has left Brazil far behind in global assessments of the consequences of GECs on coastal ecosystems. In contrast, the Brazilian coastline has vegetated ecosystems (mangroves, salt marshes, and seagrass and rhodolith beds) that together contain hundreds of millions of tons of stored carbon, making Brazil a good place to test new mechanisms to evaluate and conserve blue carbon. To promote the development of a regional science-policy agenda to respond to the urgent demand for sound scientific advice in the face of rapid changes to marine coastal ecosystems, it is necessary to integrate baseline studies to assess the habitat distribution and quality of the ecosystems, as well as the human threats and risks associated with local and regional climate-change scenarios; promote strategic monitoring of physical and biological parameters to fill critical gaps in knowledge; and provide an early warning system of GECs to coastal communities. There is also a need to refine regional and local scenarios of threats related to GECs, to assess the uncertainties, risks and thresholds at the organism and ecosystem levels.

It is imperative to integrate Brazilian researchers and institutions in order to promote the consolidation of existing knowledge and the implementation of a broad and continuous observational network. The Network for Monitoring Benthic Coastal Habitats (ReBentos) was created to detect the effects of regional and global environmental changes on benthic habitats, by creating a time-series of data on biodiversity along the Brazilian coast. ReBentos is linked to the Coastal Zones Branch of the Climate Network, hosted by the Ministry of Science, Technology and Innovation, and the National Institute of Science and Technology for Climate Change. The network was supported in its early phase by the National Counsel of Technological and Scientific Development (CNPq), São Paulo Research Foundation (FAPESP), and Coordination for the Improvement of Higher-Education Personnel (CAPES). Currently, ReBentos (http://rebentos.org/) comprises 166 active researchers along the entire Brazilian coast, belonging to 57 educational/research institutions, both national and international, and 17 coastal states.

The strategy adopted by ReBentos was to define standardized methods for biodiversity sampling, processing and data analysis, and for measuring abiotic and anthropogenic factors. The free-access e-book *Protocolos para o Monitoramento de Habitats Bentônicos Costeiros* (in English: Protocols for Monitoring Benthic Coastal Habitats; http://books.scielo.org/id/x49kz) recommends simple, rapid and low-cost methods for continuous and long-term monitoring in the diferente benthic habitats along the Brazilian coast. Based on this monitoring effort, an inventory will be assembled to increase knowledge of marine biodiversity along the Brazilian coast, and eventually to allow understanding of possible changes in the biota due to natural and/or anthropogenic events, within the context of GECs.

As a parallel strategy, ReBentos realized the need to develop a broad understanding of current knowledge on the coastal marine benthic biodiversity in different habitats along the Brazilian coast, as well as their particular susceptibilities to potential impacts of GECs. The synthesis of knowledge presented in this special issue emerges from this need, with nine articles covering different habitats including estuaries, the macrofauna and meiofauna of sandy beaches, rocky shores, coral reefs, mangroves and salt marshes, rhodolith and seagrass beds and education.

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These reviews followed general guidance from the ReBentos coordinators regarding the logical structure, with a description of the habitats including their characterization, distribution along the coast, ecosystem services, and potential responses to local and global threats. They also integrate existing knowledge regarding biodiversity studies and their historical evolution, location, spatial and thematic gaps, methods employed, existence of time series, and approaches related to the evaluation of the effect of GECs.

As ReBentos also has an environmental-education strategy aiming to develop a discussion on the issue of GECs on marine and coastal ecosystems, in order to foster and encourage changes in attitudes and values in relation to these environments and their biodiversity, a review of the approaches and initiatives undertaken along the Brazilian coast was also prepared and incorporated into this volume.

The preparation of this special issue on the synthesis of knowledge of coastal marine biodiversity and the effects of GECs on the Brazilian coast constitutes an important milestone for coastal benthic research in Brazil, providing a broad overview of the current state of knowledge. The gaps identified in both the geographical and thematic aspects influenced the selection of the sites that are being monitored by ReBentos, as well as environmental education initiatives. We believe that this special issue will play an important role in supporting future studies on biodiversity and GECs in Brazilian coastal habitats.

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General Coordinators, ReBentos

Brazilian sandy beaches: characteristics, ecosystem services, impacts, knowledge and priorities

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Abstract

Sandy beaches constitute a key ecosystem and provide socioeconomic goods and services, thereby playing an important role in the maintenance of human populations and in biodiversity conservation. Despite the ecological and social importance of these ecosytems, Brazilian sandy beaches are significantly impacted by human interference, chemical and organic pollution and tourism, as well as global climate change. These factors drive the need to better understand the environmental change and its consequences for biota. To promote the implementation of integrated studies to detect the effects of regional and global environmental change on beaches and on other benthic habitats of the Brazilian coast, Brazilian marine researchers have established The Coastal Benthic Habitats Monitoring Network (ReBentos). In order to provide input for sample planning by ReBentos, we have conducted an intensive review of the studies conducted on Brazilian beaches and summarized the current knowledge about this environment. In this paper, we present the results of this review and describe the physical, biological and socioeconomics features of Brazilian beaches. We have used these results, our personal experience and worldwide literature to identify research projects that should be prioritized in the assessment of regional and global change on Brazilian sandy beaches. We trust that this paper will provide insights for future studies and represent a significant step towards the conservation of Brazilian beaches and their biodiversity.

Descriptors: Sandy beaches, Brazil, Macrofauna, Conservation, Coastal ecosystem.

Resumo

As praias brasileiras fornecem bens e serviços ecossistêmicos fundamentais, desempenhando papel importante para a manutenção de populações humanas e para a conservação da biodiversidade. Entretanto, apesar da sua importância ecológica e social, essas praias são amplamente impactadas por alterações humanas, turismo, poluição química e orgânica e mudanças climáticas globais. Esses fatores tornam urgente a melhor percepção e compreensão das mudanças ambientais nas praias brasileiras, assim como de suas consequências na biota. Com o objetivo de promover estudos integrados que possam detectar variações nas características das praias e de outros habitats bentônicos do litoral do Brasil, foi estabelecida a Rede de Monitoramento de Habitats Bentônicos Costeiros (ReBentos). Para fornecer subsídios para o planejamento amostral da ReBentos, realizamos um intenso levantamento sobre os estudos conduzidos nas praias brasileiras e sintetizamos o atual conhecimento relativo a esse ambiente. Os resultados do levantamento são apresentados no presente trabalho e demonstram as principais características físicas, biológicas e socioeconômicas dessas praias. A partir das informações, assim como de nossa experiência e de pesquisas realizadas em diversos países, apontamos estudos e medidas que devem ser considerados prioritários para a avaliação dos efeitos das mudanças regionais e globais sobre as praias brasileiras. Esperamos que esse trabalho possa fornecer subsídios para futuros estudos e que constitua um importante passo em direção à conservação das praias do Brasil e de sua biodiversidade.

Descritores: Praias areianosas, Brasil, Macrofauna, Conservação, Ecossistemas costeiros.

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INTRODUCTION

Sandy beaches are the dominant coastal environment in most tropical and temperate regions (MCLACHLAN; BROWN, 2006). They are one of the marine environments most accessible to humans and are, consequently, very popular places for recreation. Due to these characteristics, beaches are the coastal environment most used by human populations and they sustain the economy of many cities around the world (KLEIN et al., 2004).

Although sandy beaches are primarily valued for their economic and recreational features (SCHLACHER et al., 2007), they are home to a diverse biota and provide basic goods and ecosystem services for environmental balance (DEFEO et al., 2009). The biological communities of sandy beaches are dominated by small organisms and structured mainly by the physicochemical characteristics of the environment, such as wave energy, tidal regime, slope, grain size, salinity, and dissolved oxygen (MCLACHLAN; BROWN, 2006). Consequently, the biota varies from beach to beach, and environmental, natural, or anthropogenic changes can have significant effects on the structure and functioning of a beach's biological communities.

The Brazilian coast extends for approximately 10,800 km - from Cape Orange (4ºN) to Chui (34ºS) - and has one of the largest collections of sandy beaches in the world. Contrary to their great geographical extent, knowledge about Brazilian beaches is reduced, and the information available on their biodiversity is insufficient to ensure their preservation. In addition to this limited knowledge, Brazilian economic development has historically consisted of poorly planned exploitation of natural resources, which has subjected Brazilian beaches to several types of human impacts that carry a high risk of biodiversity loss (AMARAL; JABLONSKY, 2005; SCHLACHER et al., 2008; SCHERER, 2013). Added to this are the effects of global climate change, thus, understanding Brazilian sandy beach ecosystems and predicting their response to possible environmental change has become increasingly critical and urgent.

To promote the implementation of integrated studies to detect the effects of regional and global environmental change on beaches and on other benthic habitats of the Brazilian coast, Brazilian marine researchers have established The Coastal Benthic Habitats Monitoring Network (ReBentos) (www.rebentos.org). One of the main objectives of ReBentos is the long-term monitoring of benthic biodiversity on the Brazilian coast, an approach that will generate a series of data that can be used to better understand environmental changes and their effects on the biota, as well as in the adoption of effective management and conservation strategies.

In order to summarize current knowledge on Brazilian beaches and to provide input for the future sampling design for research and monitoring by ReBentos, we conducted an intensive review of the studies performed in this environment. The results of this survey revealed that knowledge about Brazilian beaches is scant and much effort is needed to better understand and preserve this ecosystem. Here, we have combined these results, our personal experience and worldwide literature, to (1) physically characterize Brazilian beaches, (2) discuss their ecosystem goods and services, and (3) the main impacts and threats to these beaches, (4) determine the current body of knowledge on the biota of beach ecosystems and the knowledge gaps, (5) evaluate the applicability of this knowledge in identifying and predicting the effects of climate change, and (6) highlight the priorities for future studies for the conservation of Brazilian beaches and their biodiversity.

MATERIAL AND METHODS

To evaluate research on Brazilian sandy beaches, we searched for the following combination of keywords in the ISI Web of Science®, SCOPUS, and Google Scholar databases (timespan = all years; field = topic): Brazil* AND (beach* OR shore*) AND (benth* OR macrofauna). Only papers published in scientific journals and whose purpose was related to the ecology of benthic macrofauna of sandy beaches were selected. Articles with exclusively taxonomic approaches have not been included. The compilation was complemented by searching for references cited within selected articles, and by gathering information from Lattes Platform (the Brazilian researchers' scientific production system). We also sent the list of selected papers to researchers of institutions based along the Brazilian coast for them to complement the data.

To physically characterize Brazilian beaches (objective 1), we used the classification proposed by AB'SÁBER (2003) (see below). Studies about ecosystem goods and services provided by Brazilian beaches (objective 2), as well as researches on the main impacts and threats to this ecosystem (objective 3) are scant; therefore, the discussion of these topics has been based on our personal experience and worldwide studies. To determine current knowledge on Brazilian sandy beaches (objective 4), and to discuss their priorities and perspectives (objectives 4-6), the selected studies were classified according to 1) geographic region (N, NE, SE, and S), 2) primary focus (population, community, and impact), 3) publication date, and 4) sampling frequency (months to years and number of sampling events during the study) (Annex 1: http://www.io.usp.br/index.php/arquivos/send/337-vol-64-special-issue-2-2016/3909-annex-933).

RESULTS AND DISCUSSION

Physical characteristics of Brazilian beaches

Beaches are dynamic environments strongly influenced by physical factors such as wave action, tides, and sediment type. Different combinations of these factors determine the morphodynamic characteristics of the beaches and result in a wide variety of types, from reflective beaches (with steep slopes, composed of coarse sand, and having a tidal range of up to 2 m) to tidal flats (with gentle slopes, composed of fine grained sand, and usually having a tidal range above 4 m) (DEFEO; MCLACHLAN, 2005; MCLACHLAN; BROWN, 2006).

Because of the large latitudinal extent of its coast and the influence of various tidal and climatic patterns, Brazil has a large variety of beaches. Beaches range from just a few meters to more than 200 km in length, such as Cassino Beach (RS). The morphodynamic characteristics of these beaches are defined by regional climatic and oceanographic conditions, which do not coincide with the regional or political division of Brazil. Thus, a more appropriate categorization of the Brazilian coast by using its geomorphological and phytogeographic characteristics was undertaken by AB'SÁBER (2003), who divided it into six sectors: Equatorial Amazonian Coast, North Northeast, East Northeast, East, Southeast, and South.

The Equatorial Amazonian Coast covers the states of Amapá, Pará, and Maranhão and extends for approximately 1200 km, comprising more than 15% of the Brazilian coast (ISAAC; BARTHEM, 1995). This area is characterized by low relief and broad coastal plains dominated by semidiurnal macro-tides with a mean range of 4.5 m (maximum of 7 m in Maranhão, 6 m in Pará, and 12 m in Amapá) (SOUSA et al., 2011). The combination of low relief and macro-tides favors the occurrence of low-water terraces and muddy tidal flats in this region. The sandy beaches are predominantly intermediate or dissipative (EL-ROBRINI et al., 2006). The Amazon River divides the sector into two segments: the north (Amapá and northwestern Pará), with abundant muddy plains, and the south (northeastern Pará and Maranhão), with sandy and sandy-muddy beaches, mud flats and a predominance of mangrove forests (SZLAFSZTEIN; LARA, 2002). The vast majority of intertidal beaches are wide (between 200 and 500 m) and, due to the abundance of rivers flowing down to the coast, salinity is generally low (less than 30) and follows the seasonal variations in rainfall during the rainy season, reaching more than 35 in the dry months and less than 10 in the rainy months (SILVA et al., 2011).

The northeastern coast is the longest among those of all Brazilian regions (approximately 40% of the entire coast) and has a diverse landscape and relief, with the presence of several types of beaches dominated by semidiurnal meso-tides (ranging between 2 and 4 m). As half of this coast faces northwards and half eastwards, it has been divided into the northern sector of the Northeast and the eastern sector of the Northeast.

The northern sector of the Northeast comprises northeastern Maranhão, Piauí, Ceará, and northern Rio Grande do Norte and is characterized by large expanses of beach in front of sandy ridges (sandbanks) and dunes (MATTHEWS-CASCON; LOTUFO, 2006). In its western region, this sector is dominated by intermediate beaches with bars and grooves, while the eastern region is dominated by dissipative beaches and is characterized by a rockier shore with an extensive coastal tableland that borders the ocean with cliffs and paleocliffs. A peculiarity observed in the eastern region of this sector is the meeting of the caatinga (a desert vegetation) with the sea, a phenomenon rare anywhere in the world.

The eastern sector of the Northeast (east of Rio Grande do Norte, Paraíba, Pernambuco, and Alagoas) comprises a strip of sandy coves and shallow shelf edges, dominated by narrow beaches that are partly located between sandstone reefs (AB'SÁBER, 2003), which are often associated with calcareous algae and corals. These sandstone reefs form strands parallel to the coast and can reach several kilometers in length, protecting the coast from high energy coastal dynamics and creating a great diversity of landscapes such as beaches directly exposed to wave action, protected beaches, rocky coasts, areas with prairie marine grasses, and tidal flats with mangrove vegetation.

The Eastern sector covers the beaches of Sergipe, Bahia, and northern Espírito Santo, and like the northeastern coast, is subject to a climatic regime of semidiurnal meso-tides. This sector presents large continuous stretches of almost rectilinear form, with beaches of fine to very fine sand in front of shelves, arched deltas, and dune fields. During the summer, a dry season when the Disturbed Eastern Currents (Eastern Waves) have a strong influence, the morphodynamic beach states alternate between dissipative and intermediate (with a depositional trend). During the winter, when there is an increased frequency of rainfall, the dissipative state predominates due to the increased wave energy associated with the advance of cold fronts.

The Southeast sector (central south of Espírito Santo, Rio de Janeiro, São Paulo and Paraná) is the most diverse and rugged coastal macro-sector in the country and is influenced by a semidiurnal micro-tidal regime. In general, this sector presents distinct morphological characteristics between its northern and southern regions. The northern region (central south of Espírito Santo to the northern region of São Paulo) has a highly indented coastline, composed of bays and coves, and a dominance of reflective beaches, with coarse particle sizes, high sloping beach faces, and almost no surf zone. The southern section (south of São Paulo and Paraná) is characterized by a rather homogeneous, rectilinear coastline and high energy dissipative beaches with wide intertidal zones, low inclination, a predominance of fine sand, and homogeneous, plane beach profiles (AMARAL; BORZONE, 2008).

The configuration of the South sector (Santa Catarina and Rio Grande do Sul) begins with the end of the forested escarpments of the Serra do Mar on the border between Paraná and Santa Catarina. It is the second most ragged section of the Brazilian coast (especially in its northern portion) and, like the Southeast sector, is subject to a micro-tidal regime. The southern portion of this sector ends in a long, wide rectilinear coastline, dominated by dissipative and intermediate beaches as far as the Uruguayan border. In this southern stretch of the sector, there is prominent spatial variability in the morphodynamic and textural characteristics, with the presence of bimodal sediment beaches composed of fine sand and organic debris (BARROS et al., 1994). Due to the frequent passage of strong cold fronts and cyclones during the winter (KRUSCHE et al., 2002), the beaches of the southern region are strongly influenced by the winds of the quadrant (CALLIARI; KLEIN, 1993; PARISE et al., 2009).

Ecosystem goods and services provided by Brazilian beaches

Beaches provide many fundamental ecosystem goods and services such as storage and transport of sediment, shoreline protection, filtration of large volumes of water, and nutrient cycling (SCHLACHER et al., 2008; DEFEO et al., 2009). In addition to these services, Brazilian beaches provide socioeconomic goods and services that are essential for human populations, particularly related to fishing and tourism (PROJETO ORLA, 2002).

Shellfish harvesting in the intertidal region, and fishing with drag nets in the surf zone are one of the main activities carried out by coastal populations and are widespread practices throughout Brazil. As sandy beaches are used for the launching and beaching of small boats, they also have a fundamental role in fishing near the coast. Due to their scenic beauty and the tropical climate characteristic of most of Brazil, the Brazilian beaches represent ideal places for rest and recreation; thus, many coastal cities have a tourism-based economy. Furthermore, some Brazilian beaches provide other goods and services, including the cultivation of seaweed and crustaceans, the exploitation of sea salt (especially in the northeastern region of the country), and the cultivation of molluscs (mainly in Southern Brazil).

Brazilian beaches also play a significant role in biodiversity conservation by providing landing sites, foraging habitats, and nesting grounds for a large number of terrestrial and marine organisms, including several species of birds (VOOREN; CHIARADÍA, 1990; VOOREN, 1998; RODRIGUES, 2000; BARBIERI; HVENEGAARD, 2008; AZEVEDO JÚNIOR; LARRAZABAL, 2011) and five species of turtle: *Chelonia mydas* (green turtle), *Eretmochelys imbricata* (hawksbill turtle), *Caretta caretta* (loggerhead turtle), *Lepidochelys olivacea* (olive ridley turtle), and *Dermochelys coriacea* (leatherback turtle) (MARCOVALDI; MARCOVALDI, 1985, 1999).

Impacts

Because sandy beaches are impacted by both terrestrial and marine environments, they are among the most vulnerable ecosystems. In Brazil, the main sources of disturbance to sandy beaches are (1) human interference (road construction, real estate, groins, breakwaters, sea walls, etc.), (2) chemical and organic pollution, and (3) tourism.

Since the early twentieth century, particularly in the Southeast, development and landfills have profoundly transformed the coastal landscape. Large expanses of beaches and dunes have been eliminated to allow the construction of buildings, which has compromised the beach ecosystem in many regions. Even today, these transformations are carried out constantly, with large coastal restoration projects, real estate developments, and roads being constructed along the coast, especially on the dunes and backshore. The construction of walls or barriers to protect the coastline is also a frequent human interference along the Brazilian coast. Although these structures are built to protect the region beyond the barrier, they modify the transport of sand within beaches and from beach to beach, which increases the erosion process (MUEHE, 2003; 2006).

Urban, industrial, and port development also have an impact on Brazilian beaches. Due to a lack of regulation or to disrespect for existing legislation, cities and industries dump waste rich in organic and inorganic compounds directly into the sea or rivers that flow into the ocean, thereby altering the physico-chemical characteristics of the water and causing an oxygen deficit in the sediment. Industrial activities on the beaches or in nearby areas, as observed in salt production facilities and shrimp farms in the northeast, also trigger changes in beach biota. Port activities may be associated with the release of waste or antifouling compounds, leakage, dredging of access channels, and introduction of exotic species. As a result, there has been a reduction in faunal diversity and an increase in the dominance of a few tolerant species in areas near beaches surrounded by intense urban development, particularly in industrialized and port areas (OMENA et al., 2012).

Although it is an essential source of income for many cities, tourism is another pressure on Brazilian beaches. The movement of vehicles and intense trampling, especially in the upper littoral and supra-littoral zones, eliminates species and interferes with the breeding and nesting of birds (VELOSO et al., 2008; DEFEO et al., 2009; VIEIRA et al., 2012). Litter left behind by beachgoers - if not taken out to sea, leading to the contamination of islands and oceans - is usually removed by mechanical cleaning. During this process, not only the waste but also the sand and all the fauna and organic matter associated with it are removed, thereby reducing populations and communities, and changing the trophic processes and energy cycling within the ecosystem (BORZONE; ROSA, 2009; DEFEO et al., 2009).

In addition to the impact of human activities on land, beaches are among the most vulnerable marine environments to the impacts of global climate change such as rising sea level, increased frequency and magnitude of extreme events, coastal erosion, rising sea temperatures, and ocean acidification. The Intergovernmental Panel on Climate Change highlights that human interference with the climatic system is already occurring and has resulted in the disturbance of natural systems on all the continents and in all the oceans (IPCC, 2014). Current predictions for the effects of climate change on the Brazilian coast, while heterogeneous, indicate increased air and sea-surface temperatures, and rising sea levels throughout national territory (RAICICH, 2008; MARENGO et al., 2010). Although the exact magnitude of the impact of these changes on the beaches is not yet clearly defined, related ecological changes (e.g., changes in phenology, physiology, and distribution of species) are increasingly evident (DEFEO et al., 2009).

The forecasting and modeling performed in several studies indicate that changes in global temperature will result in rising sea levels and an increase in the frequency and intensity of extreme events such as cold fronts associated with extratropical cyclones. These effects may promote erosion of the coastline, flooding by storm surge, changes in tidal amplitude, and changes in sedimentary patterns (CALLIARI; KLEIN, 1993; CALLIARI et al., 1998; MUEHE, 2006). These impacts may result in changes to the biota and morphodynamics of beaches in the short and long term as a result of changes in the composition of the sediment, slope, area available for occupation by the organisms, and, in extreme conditions, the loss of intertidal and backshore areas (SOLA; PAIVA, 2001; GALLUCI & NETO, 2004; NEGRELLO FILHO, 2005; COCHOA et al., 2006; ALVES; PEZZUTO, 2009; DEFEO et al., 2009). Variations in rainfall distribution may modify the solid discharge (sediment) from rivers and the volume of fresh water that reaches the oceans, also contributing to changes in the morphodynamics of beaches and the salinity of seawater. Ocean acidification will reduce calcification rates and calcium metabolism in marine organisms, including various species of molluscs and crustaceans present on beaches (DEFEO et al., 2009). In addition, an increase in temperature can cause excessive harmful algal blooms, which will influence the quality of the coastal region (TURRA et al., 2013).

As the beaches of southern Brazil are highly influenced by the ENSO phenomenon (El Niño Southern Oscillation - El Niño and La Niña), they may be the most affected by global climate change. MUEHE (2003) emphasizes that in Rio Grande do Sul, waves rarely exceed 2 m; however, during the passage of cold fronts, the waterline can reach the base of the dunes (approximately 1.7 m above the mean level) and may significantly increase their erosive potential (CALLIARI et al., 1998). In addition to changes in topographic profiles, extreme events can also cause massive mortality of biota, mainly due to embankments (entrapment of organisms in the swash zone in the upper beach zones) (DEFEO; CARDOSO, 2002; SILVA et al., 2008).

Current knowledge of Brazilian beaches

A total of 126 published studies on the ecology of the macrofauna of sandy beaches was recorded. These studies were conducted on 172 beaches over a period of approximately forty years, the first of them being published in 1976 (Annex 1: http://www.io.usp.br/index.php/arquivos/send/337-vol-64-special-issue-2-2016/3909-annex-933). Studies were recorded on the four Brazilian coastal regions; however, the number of publications relating to each of the regions is quite unbalanced (Annex 1: http://www.io.usp.br/index.php/arquivos/send/337-vol-64-special-issue-2-2016/3909-annex-933, Figure 1). Approximately 84% of the studies were conducted in the southeastern and southern regions (n = 107), while only 2% (n = 3) evaluated beaches in the northern region. This discrepancy can be attributed mainly to the degree of occupation and development of each region. The installation date and number of universities, as well as the resulting presence of experts, are other factors that contribute to such differences between regions in the number of studies conducted.

Investigations were also clustered within each region. Due to logistical conveniences, the studies were mostly conducted on beaches close to universities or research centers. The best example of this concentration is the state of São Paulo, which has the largest number of studies conducted on sandy beaches among the Brazilian states; yet, little or nothing is known about most of its coastline (Figure 1). Almost all studies on the São Paulo coast have focused on northern beaches, an area that has the support of the University of São Paulo (USP). The local concentration of studies, however, is not unique to the São Paulo beaches. In the northeastern region, the studies have focused mainly on certain beaches in Ceará and Pernambuco; in the southeastern region, apart from the north coast of São Paulo, most studies have been performed on beaches located in the city of Rio de Janeiro; while in the southern region, the studies were conducted mainly in the regions of Pontal do Paraná (PR), Babitonga Bay (SC), and Cassino Beach (RS).

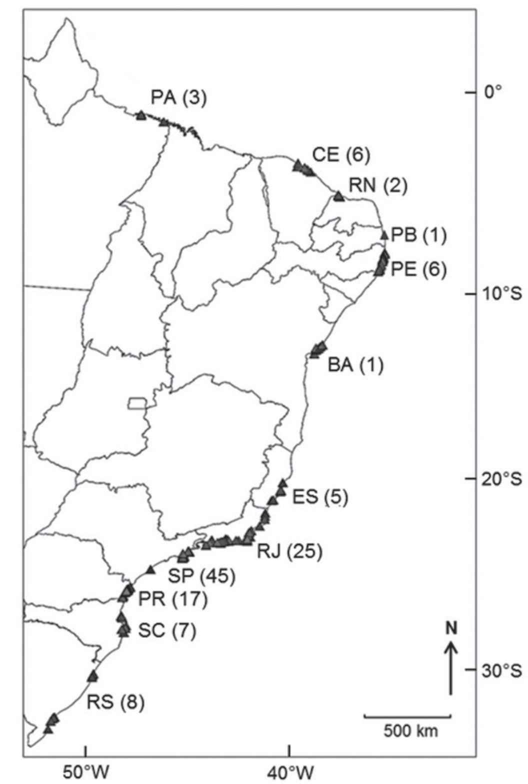

Figure 1. Location map of Brazilian beaches studied in published papers on benthic ecology. Numbers in parentheses correspond to the number of articles conducted in each state.

Although research on the sandy beaches of the Brazilian coast began in the 1970s, it was only in the late 1990s that the number of studies became more prominent (Figure 2). Almost all the work conducted (96%) focused on the description of population and community patterns, and linked these to environmental characteristics, particularly sediment type, salinity, and waves.

Most studies (75%) have had a duration of one year or less. Research with a monthly sampling regime covering 12 months has been the most frequent and has accounted for 50.4% of the total number of studies analyzed, while 26.4% of the studies were performed by collecting only one sample per beach. Approximately 17.6% of the studies have had a duration of up to two years and only seven (5.6%) lasted more than two years.

Species with broad geographic distributions, such as the crustaceans *Emerita brasiliensis*, *Excirolana brasiliensis* (PAGLIOSA et al., 1998; CARDOSO et al., 2003; VELOSO; CARDOSO, 1999; PETRACCO et al., 2003; CAETANO et al., 2006; EUTRÓPIO et al., 2006), and *Ocypode quadrata* (TURRA et al., 2005; BLANKENSTEYN, 2006; NEVES; BEMVENUTI,

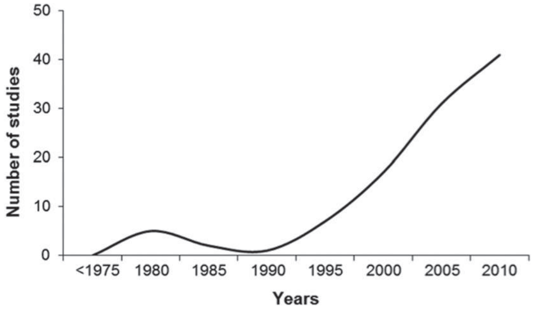

Figure 2. Number of published papers on benthic ecology of Brazilian beaches since 1970.

2006; ARAUJO et al., 2008; SOUZA et al., 2008; MAGALHÃES et al., 2009; POMBO; TURRA, 2013), the bivalve *Anomalocardia brasiliana* (ARRUDA-SOARES et al*.,* 1982; NARCHI, 1976; BARREIRA; ARAUJO, 2005; LUZ; BOEHS, 2011; MATTOS; CARDOSO, 2012; RODRIGUES et al*.,* 2013; BELÉM et al., 2013; CORTE et al., 2014, CORTE, 2015; CORTE et al. 2015), and the polychaetes *Scolelepis* spp (SANTOS, 1991, 1994; SOUZA, BORZONE, 2000; MACCORD, AMARAL, 2007; LEÃO et al., 2012) were the most studied species.

Although the number of studies on Brazilian beaches does not allow adequate evaluation of the existing biodiversity in this environment, some patterns in the spatial distribution of the most frequently studied species can be established (Figure 3). The crustaceans *Atlantorchestoidea brasiliensis* and *Ocypode quadrata* and the insects *Bledius* spp are some of the most common species in the supra-littoral zone of Brazilian beaches, while the bivalves *Anomalocardia brasiliana* and *Donax hanleyanus*, the crustacean *Emerita brasiliensis*, and the polychaetes *Capitella* spp and *Scolelepis* spp are often found in the mid-littoral zone. In the infra-littoral zone of many Brazilian beaches, the sand dollar *Mellita quinquiesperforata* and the bivalve *Tellina* spp are common.

Priorities and perspectives

The great heterogeneity of Brazilian beaches and the limited knowledge of their biodiversity highlight the urgent need for further studies to gain a better understanding of this ecosystem. Basic faunal surveys, aimed at biodiversity assessment, are still required in all Brazilian regions, especially in the northern and northeastern regions. In the southeastern and southern regions, a better distribution of studies is necessary to make a better visualization of the local and regional heterogeneity of the beaches possible.

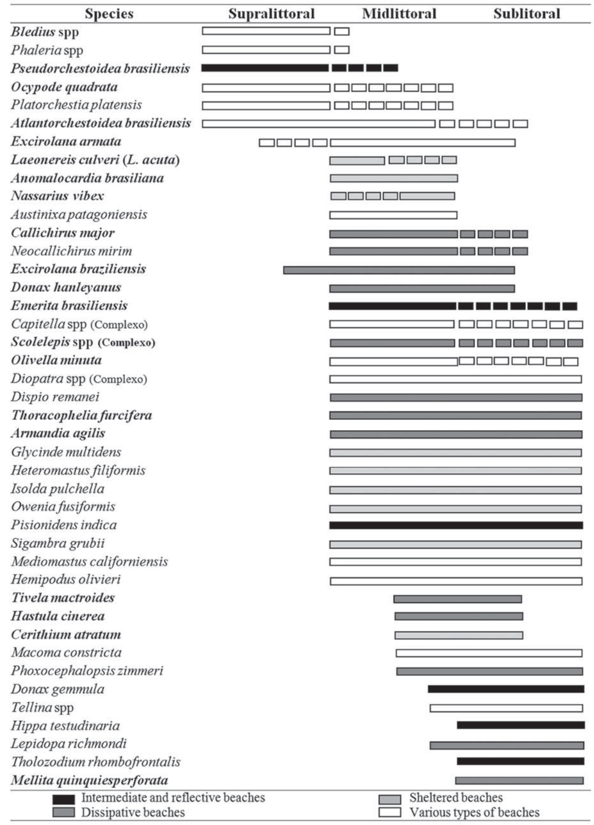

Figure 3. Spatial distribution of dominant species along Brazilian beaches. Names in bold indicate species for which population studies have been conducted.

In addition to studying a broader range of areas, temporal replication of sampling is necessary to allow the compilation of long-term data series. The dominance of studies having a duration of less than one year (many with only one sample collection per area) brings out the sparse temporal replication of studies conducted on Brazilian beaches and highlights the need to work with long-term data series. Several processes related to populations and communities of benthic macrofauna, such as recruitment, zonation, and intra- and inter-specific interactions, may change at intervals of years or decades, and only from long-term monitoring can one achieve a better understanding of active processes on beaches and refine the existing hypotheses (TURRA et al., 2014).

Standardization of the methodologies used and the systematic application of monitoring protocols for large spatial and temporal scales is an essential strategy required to ensure environmental changes such as habitat degradation, reduced primary and secondary productivity, and biological invasions are documented (TURRA et al., 2013). From this homogeneous and long-term approach, consistent data will be obtained, which will serve as a baseline for descriptive and predictive modeling of the responses of benthic communities under different scenarios of global and regional changes, in addition to formulating proposals for corrective action. In this context, the ReBentos Beaches Working Group, following methodological and logistical discussions, formulated a number of protocols for the long-term monitoring of some of the most widespread and common species (Polychaeta: *Scolelepis*; Maxillopoda: Talitridae, *Ocypode quadrata*; Insecta: *Bledius*) as well as of macrofaunal communities on Brazilian beaches (http://www.rebentos.org). These protocols were formulated with readiness, methodological simplicity, and low cost in mind, and they are an important step towards achieving the necessary knowledge to understand and conserve the biodiversity of Brazilian beaches.

In addition to descriptive studies, field and laboratory experiments are necessary to understand differences resulting from anthropogenic impacts and climate change. Mensurative and manipulative experiments have been used to assess the impacts of anthropogenic activities such as vehicle traffic, recreation, construction of breakwaters, and nourishment on the macrofauna of sandy beaches, and their results have contributed significantly to a better understanding of the strength and resilience of this ecosystem (BARROS, 2001; BESSA et al., 2013). Assessments before and after the occurrence of extreme events, with adequate temporal and spatial replication, (see UNDERWOOD; CHAPMAN, 2005 and included references) can provide key information to help understand these phenomena and their consequences.

Studies on the secondary production of key species should be intensified because they are essential to the understanding of processes of energy transfer in the ecosystem of sandy beaches (PETRACCO et al., 2012; 2013). Research on the physiology and gene expression patterns of the species that occur on sandy beaches should also be encouraged. Given that the ability of a species to cope with changes in its environment is related to its complement of genes (SOMERO, 2010), the integration of biological, ecological, and environmental data with biomolecular processes can be an effective tool for the verification of the effects of environmental change on different species, thereby creating a basis for predicting how adaptive evolution can occur in response to global climate change (SOMERO, 2010; LOCKWOOD et al., 2010; LOCKWOOD; SOMERO, 2011).

Improved interactions between scientists and decision makers are also essential for efficient management and conservation strategies to be formulated and applied. Often, conducting medium- and long-term studies is plagued by a lack of resources, which could be more easily obtained if there were a collaborative framework between managers and promoters. On the other hand, the decisions made by managers may be more accurate if they were supported by scientific evidence. More effective collaborations among researchers from different institutions and disciplines is also another key aspect in the training of students with better analytical capabilities (TURRA et al., 2013), as well as seeking to improve the understanding of current researchers. Evaluation of a wide range of physicochemical characteristics and biological components will allow for a comprehensive understanding of sandy beaches and will enable effective measures to be taken in the near future.

Conclusion

Brazil has a large and diverse number of sandy beaches which play a key role in biodiversity and the support of human populations. Despite their importance, knowledge about these beaches is sparse, and Brazilian historical and socioeconomic characteristics endanger this ecosystem. To gain a better understanding of Brazilian beaches, systematic and long-term studies are required on multiple scales. Experimental and population studies and/or those that incorporate biological, ecological, and environmental data with biomolecular processes should also be encouraged and will add important information to the understanding of Brazilian beaches and their biodiversity. Improved interactions among scientists and decision makers must be pursued as these may facilitate further studies and could lessen the impact of some policy measures. Only on the basis of a better understanding of Brazilian beaches can the real impacts of environmental change be understood and effective measures to conserve this ecosystem be proposed.

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State of the art of the meiofauna of Brazilian Sandy Beaches

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Abstract

In Brazil, meiofauna studies began in the middle of last century, but they adopted a purely taxonomical approach, describing species from various zoological groups. After this first step, this benthic group was largely neglected until the end of the 20th century when ecological studies began. We here provide a brief review of present knowledge of the meiofauna found on Brazilian sandy beaches to provide information for ReBentos (Coastal Benthic Habitats Monitoring Network). Our methodology consisted of a bibliographic survey undertaken using different datasets (Web of ScienceTM, SCOPUS, Google Scholar and Lattes Plataform). For the survey, we considered only those studies published till early 2015. Our analysis showed that the number of meiofauna studies has increased over the last two decades, though they are mainly still concentrated on the Southeast of Brazil. These studies aim to explain the distribution pattern of the meiofauna of the intertidal region of sandy beaches. Based on the results, we presented a discussion of three main topics, i.e., (a) current knowledge of Brazilian sandy beach meiofauna, (b) sampling strategies for monitoring of the meiofauna, and (c) use of the meiofauna as a tool to assess climate change. We trust that this brief review will be useful as a starting point for the delineation of further climate change investigations into sandy beach meiofauna.

Descriptors: Sandy beaches, Meiofauna, Biodiversity, Monitoring, ReBentos, Climate change.

Resumo

No Brasil, os estudos da meiofauna iniciaram em meados do século passado, com enfoque puramente taxonômico e voltado para a descrição de espécies de diferentes grupos zoológicos. Após essa fase inicial, a biota foi de certa forma esquecida até o final do século XX, quando os estudos ecológicos foram iniciados. Neste trabalho apresentamos uma breve revisão do conhecimento sobre a meiofauna de praias arenosas brasileiras, com o objetivo de fornecer subsídios para a ReBentos (Rede de Monitoramento dos Habitats Bentônicos Costeiros). Para isto, nossa metodologia envolveu um levantamento bibliográfico realizado a partir de diferentes bases bibliográficas (Web of Science®, SCOPUS, Google Scholar e Plataforma Lattes), considerando artigos publicados até o início de 2015. As análises mostraram que o número de estudos da comunidade da meiofauna se intensificou nas últimas duas décadas, concentrando-se, principalmente, na região Sudeste do Brasil. Esses estudos visaram explicar os padrões de distribuição dos organismos na região intermareal. Com base nisso, apresentamos uma discussão desses resultados em relação a três principais temas: (a) conhecimento atual da meiofauna nas praias arenosas brasileiras, (b) estratégias amostrais para o monitoramento/estudo da meiofauna e (c) as perspectivas do uso da meiofauna na avaliação das mudanças climáticas. Espera-se que esta breve revisão possa ser usada como um estágio inicial para o delineamento de estudos que abordem o impacto das mudanças climáticas sobre a meiofauna de praias arenosas.

Descritores: Praias arenosas, Meiofauna, Biodiversidade, Monitoramento, ReBentos, Mudanças climáticas.

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INTRODUCTION

The term "meiofauna" is used to denote a heterogeneous group of benthic organisms that belong to a specific size class represented in almost all invertebrate phyla. In general, meiofauna organisms are able to pass through a mesh sieve of 500 µm or 1 mm (size limits used depend on the author and the purposes of the study), but are retained by a mesh size of 62-38 µm during an extraction procedure (GIERE, 2009). The term meiofauna was coined by MARE (1942) despite not having any special taxonomical or ecological significance (FENCHEL, 1978). Among the meiofaunal organisms, nematodes represent the majority of individuals in a sample of marine sediments (HEIP et al., 1985) and this is indeed true for the dynamic sandy beach ecosystem.

Sandy beaches are dynamic ecosystems driven by physical processes that shape the habitat for different functional and taxonomic groups. The term "sandy beach" can be used to describe a wide range of environments, from high-energy open-ocean beaches to sheltered estuarine sand flats (MCLACHLAN, 1983). Sandy beaches are, in general, dynamic environments occurring worldwide along ice-free coastlines, and located at the transition between the land and a waterbody such as an ocean, sea or lake. At first sight, this ecosystem seems to be a marine desert, due to the arid and sterile appearance of its sands. However, its wide range of habitats supports the establishment of a diverse biota, but even so this ecosystem is still less studied than most other coastal systems (DEFEO; MCLACHLAN, 2005). Most research on intertidal sandy beaches has been concentrated on macrofauna and on birds (see CORNELIUS et al., 2001; DEFEO; MCLACHLAN, 2005 for a review) and the less prominent sandy-beach meiofauna has received considerably less attention.

The first ecological study of the meiofauna in a sandy beach was undertaken on the German coast by REMANE (1933). After the development of specific methods to sample small benthos, the studies on the meiofauna have gained great importance in many parts of the world. At the present time, this group is being studied in habitats as diverse as alpine lakes and the deep-sea floor, tropical reefs and polar sea ice (GIERE, 2009). In terms of sandy beaches, the focus of the studies is mainly related to distribution patterns and few studies focus on more specific questions such as the response of nematodes to pollution and their role in the benthic food web (MARIA *in press*). In Brazil, meiofauna studies started in the middle of the last century, but were purely taxonomical, describing species of different meiofaunal groups (e.g. Platyhelminthes, Annelida, Mollusca, Nematoda, Kinorhyncha, Nemertea, Acari, Amphipoda, Ostracoda). After this taxonomical bloom, the meiofauna were neglected until the 1990s when ecological studies started (FONSECA et al., 2014).

Considering that meiofauna/nematodes have high abundance and diversity, widespread distribution, rapid generation time, fast metabolic rates, participate in the remineralization process, provide energy to higher trophic levels, they may be considered an excellent tool to evaluate environmental changes (ZEPPILLI et al., 2015). As one of the main goals of ReBentos (Coastal Benthic Habitats Monitoring Network) is to undertake a long-term monitoring of benthic biodiversity on the Brazilian coast in order to better understand the effects of environmental change on the biota, our aim is to provide a brief review of current knowledge of the meiofauna of sandy beach ecosystems which could be used as a starting point for future studies. They may, for instance, be used to provide data for the understanding of the effects of climate change on sandy beaches.

MATERIAL AND METHODS

A bibliographic survey was undertaken using Web of Science™, SCOPUS, Google Scholar, and Lattes Platform databases, considering works published until early 2015. Initially papers published in scientific journals and only those with an ecological purpose related to the benthic meiofauna community of sandy beaches were selected and enumerated. Taxonomical articles were largely excluded from the analysis. The selected studies were classified according to 1) geographical region (North, Northeast, Southeast, and South), 2) primary focus (effect of an environmental variable, impact, methodology), 3) year of publication, 4) sampling frequency (months to years and number of sampling events during the study), and 5) number of beaches sampled. All this information may be found in Table 1.

RESULTS

Although the Brazilian coast extends for approximately 8000 km and contains approximately 2000 beaches, only 2.5% of these beaches had already been studied from the point of view of the meiofauna, resulting in 44 Brazilian sandy beach meiofauna studies covering the sampling of ten estuarine and 49 oceanic beaches. Of these ecological studies, 7 are exclusively related to

Table 1. Overview of the sandy beach meiofauna studies in Brazil. Only community studies are listed.

	Author	Year	Purpose	Periodicity	Sampling duration	nº of beaches studied	State
1	MEDEIROS	1984	EVA	?	?	1	SP
2	SILVA et al.	1991	EVA	SA	2m	1	RJ
3	CARVALHO et al.	1992	EVA	?	?	1	PE
4	MEDEIROS	1992	EVA	SA	2m (3d/m)	1	SP
5	ESTEVES et al.	1995	MET	YR	1m	1	RJ
6	BEZERRA et al.	1996	EVA	MO	12m	1	PE
7	BEZERRA et al.	1997	EVA	MO	12m	1	PE
8	ESTEVES and FONSECA-GENEVOIS	1997	EVA	YR	1m	1	PE
9	ESTEVES et al.	1997	MET	YR	2m	1	RJ
10	SILVA et al.	1997	REV	n.a.	n.a.	n.a.	n.a
11	WANDENESS et al.	1997	EIE	MO	6m	1	RJ
12	ESTEVES and SILVA	1998	MET	YR	1m	3	RJ
13	ESTEVES et al.	1998	EVA	DIA	15d	1	RJ
14	WANDENESS et al.	1998	EVA	YR	1m	1	RJ
15	SILVA et al.	1999	EVA	YR	?	4	RJ
16	CURVELO and CORBISIER	2000	EVA	MO	6m	1	SP
17	CORGOSINHO et al.	2003	EVA	YR	1m	2	PR
18	MOELLMANN and CORBISIER	2003	EIE	MO	3m	2	SP
19	OLIVEIRA and SOARES-GOMES	2003	EIE	YR	1m	1	RJ
20	SOMERFIELD et al.	2003	EVA	YR	1m	1	PE
21	SOUZA-SANTOS et al.	2003	EVA	MO	12m	1	PE
22	ESTEVES	2004	EVA	MO	12m	1	RJ
23	TODARO and ROCHA	2004	EVA	YR	1m	23	SP
24	PINTO and SANTOS	2006	EVA	SA	2m	1	PE
25	ALBUQUERQUE et al.	2007	EVA	MO	12m	1	RJ
26	NETTO et al.	2007	EVA	YR	1m	1	SC
27	DI DOMENICO et al.	2008	EVA	SA	2m	6	SC and PR
28	MARIA et al.	2008b	EVA	SA	2m	3	RJ
29	GOMES and ROSA FILHO	2009	EVA	BM	4m	1	PA
30	DA ROCHA et al.	2009	EVA	S/P	5m	3	PE
31	ROSA FILHO et al.	2011	EVA	YR	1m	3	PA
32	MARIA et al.	2013a	EVA	SA	2m	2	RJ
33	MARIA et al.	2013b	EXP	YR	1m	1	SP
34	GOMES et al.	2014	EVA	BM	4m	1	PA
35	VENEKEY et al.	2014a	EVA	MO	12m	1	PE
36	VENEKEY et al.	2014b	EVA	BM	4m	1	PE
37	NETTO et al.	2014	EVA	DIA	1m	3	PR

EVA: Environmental effect; EIE: Environmental impact effect; MET: Methodological; EXP: Experimental, YR: Yearly; SA: Semiannual; BM: Bimonthly; MO: Monthly; DIA: Daily; S/P: Periodicity undefined, m: Month (s) d: Day (s); d/m: Number of days per month; n.a.: Not applicable; ?: not informed; PA: Pará; PE: Pernambuco; PR: Paraná; SC: Santa Catarina; SP: São Paulo; RJ: Rio de Janeiro.

the effects of environmental variables on the population of a single nematode species (ESTEVES et al., 2003, 2004; MARIA et al., 2008a; VENEKEY et al., 2011) and tardigrades (CASTRO et al., 1999; DA ROCHA et al., 2004; VERÇOSA et al., 2009) and have not been listed in Table 1. The other 37 are related to meiofauna community studies. As can be seen from Figure 1, the number of ecological studies has increased over the last decade.

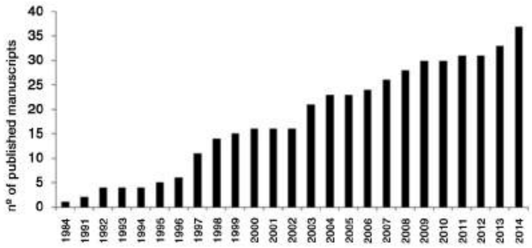

Figure 1. Cumulative percentage of the published manuscripts dealing with meiofaunal communities in sandy beaches.

Despite the great extension of the Brazilian coastline and the huge number of sandy beaches occurring along the coast, the sandy-beach meiofauna studies are restricted to only 6 Brazilian states: Pará, Paraná, Pernambuco, Rio de Janeiro, Santa Catarina and São Paulo (Table 1). However, the majority (19/37) are restricted to the Southeast region (Rio de Janeiro and São Paulo) followed by the Northeast region (Pernambuco) with 11 out of 37 studies. The studies in the Northern and Southern regions have been begun only in the last 5 and 10 years, respectively, and both together account for only 3 and 4, respectively, of the 37 studies (Table 1).

Southeast

Much of what is known of the meiofauna of Brazilian sandy beaches is concentrated in this geographical area of Brazil. Thirty-seven of the sandy beaches in this area have been sampled, the majority of them being located in São Paulo (27). Most of these studies sought to understand the meiofauna distribution in relation to physicochemical variables. Granulometry is the variable that best explains the meiofauna community in almost all pristine areas (MEDEIROS et al., 1992; ALBUQUERQUE et al., 2007) as well as in organic polluted areas (MARIA et al., 2013a); however, the degree of organic pollution affects the fauna to a different extent according to the concerned taxa, e.g. copepods are more sensitive to pollution and decrease their density while nematodes increase it (OLIVEIRA; SOARES-GOMES, 2003). However, there are cases in which the granulometry of polluted beaches seems not to influence the meiofauna composition (WANDENESS et al., 1997). The intensive trampling of the sediment, when sandy beaches are used as recreational areas, can also have a negative impact on the meiofauna community (MOELLMAN; CORBISIER, 2003). Although nematodes are the dominant meiofaunal group in sandy beach sediments, gastrotrich is another meiofaunal group which has been extensively studied in this geographical area; this group also responds to variation in grain size, showing high diversity in beaches characterized by medium and fine sand associated with little detritus and clear water (TODARO; ROCHA, 2003).

Concerning the seasonal distribution, there is some evidence that temperature and salinity fluctuations over a seasonal cycle can influence the meiofauna distribution (ESTEVES et al., 1998).

The role of biological interactions on sandy beaches are less studied since it is commonly accepted that this structural factor is of less importance in dynamic environments (DEFEO; MCLACHLAN, 2005); as a result there are only two studies related to this issue as related to southeastern sandy beaches (see CURVELO; CORBISIER, 2000; MARIA et al., 2013b). In the former one, the variation of meiofauna density between the seasons is related to the habitat heterogeneity resulting from the presence of the algae *Sargassum cymosum* on the rocky shore whereas in the latter study the presence of polychaetes – *Scolelepis* – seems not to influence the nematode community.

The Northeast

This geographical area is the second in terms of published manuscripts, but only eight beaches have been investigated, all of which are, surprisingly, located in Pernambuco state. As a result, these beaches are all subject to the mesotidal regime although this is the only geographical region of the country which contains beaches of all three tidal regimes (macrotidal, mesotidal and microtidal).

All beaches studied here are suffering from some great anthropogenic impact, such as the disposal of organic waste and recreational use as the case of Tamandaré beach, Pina Bay and the Olinda Isthmus (BEZERRA et al., 1996; SOMERFIELD et al., 2003; SOUZA-SANTOS et al., 2003) or to a lesser extent, such as Coroa do Avião and Itamaracá beaches (PINTO; DOS SANTOS, 2006; DA ROCHA et al., 2009). The spatial and temporal distribution patterns of the meiofauna are associated with environmental variables, such as pigments, granulometry and rainfall (PINTO et al., 2006; SOUZA-SANTOS et al., 2003; VENEKEY et al., 2014b) in less organically polluted areas, whereas the biochemical demand for oxygen is an important environmental variable that explains the community structure's variation in organic polluted beach sediments (SOMERFIELD et al., 2003).

There are also some studies that aim to assess the richness of copepods, tardigrades and nematodes for this geographical area (WANDENESS et al., 1998; DA ROCHA et al., 2009; VENEKEY et al., 2014a, 2014b). A higher richness of copepods is associated with the presence of sea grass on sandy beach sediments (WANDENESS et al., 1998), whereas a higher diversity of nematodes is associated with the beach level and it is found on a lower beach level (VENEKEY et al., 2014b). Unfortunately, no relationship between tardigrate richness and environmental variables was investigated (DA ROCHA et al., 2009).

The North

Knowledge of the meiofauna of the Northern region of Brazil is highly incipient, only four beaches having been sampled, and the respective studies focus on the assessment of the meiofauna of macrotidal beaches in contrast to studies undertaken in other geographical regions that sampled microtidal/mesotidal beaches. These studies also aimed to correlate the meiofauna distribution with physicochemical factors, it also being demonstrated that granulometric features are the main factor explaining its distribution - and consequently higher meiofauna density is found on exposed beaches than on sheltered ones (GOMES; ROSA FILHO, 2009; ROSA FILHO et al., 2011). Salinity also plays an important role in the temporal distribution, i. e. slightly higher richness and abundance occurred under the low salinity levels typical of the dry season of the year (GOMES; ROSA FILHO, 2009).

The South

The meiofauna studies produced in this geographical region of the country are very recent. The first meiofauna assessments date from the early 21st century and were undertaken in subtidal areas in contrast to most meiofauna studies that emphasize the intertidal area (CORGOSINHO et al., 2003; NETTO et al., 2007). Nevertheless, the results obtained for meiofauna density were similar to those found for intertidal areas, that is to say, hydrodynamic regimes influence meiofauna density, which is higher in exposed areas than in sheltered ones (CORGOSINHO et al., 2003), as well as polychaete richness and diversity (DI DOMENICO et al., 2009). The effects of food subsidies on the meiofauna are another issue which has been investigated in this geographical area. Microphytobenthos seems to be an important food source for meiofaunal organisms since chlorophyll *a* and feofitina *a* correlated positively with meiofauna density (NETTO et al., 2007) in subtidal areas while there is no robust evidence for the use of surf phytoplankton as a food source for intertidal meiofaunal organisms (NETTO et al., 2014).

DISCUSSION

Although Northeast and Southeast regions continue to be the most intensively studied as regards the meiofauna, the number of beaches investigated varies greatly as between the states of these geographical regions. This scenario is somewhat different in the southeastern region where two states have been widely studied (São Paulo and Rio de Janeiro), accounting for 37 out of 65 Brazilian beaches studied. This picture is a reflection of the existence of the first centers of meiofauna investigation that were established in the southeastern and northeastern regions. Nowadays, there are experts working on the meiofauna and conducting studies in other geographical regions, such as the States of Pará and Paraná, but it was only possible after training a new generation of scientists.

It is difficult to establish an adequate estimate of the actual species diversity of meiofauna on Brazilian sandy beaches since many of the quoted studies are based on major taxonomical groups (phylum, classes, and so on). What is well known is that biodiversity is reduced in impacted areas, but some nematode genera/species are able to withstand very harsh conditions (MARIA et al., 2013a). However, the assessment of meiofauna diversity and density is ideal on reflective sandy beaches because this group of organisms is unique in the benthic community, being able to persist with high abundances (MOORE; BETT, 1989). This group is, therefore, an ideal bioindicator candidate for evaluating the impact of climate change on reflective sandy beaches since macrofauna organisms are commonly absent on this beach type (MCLACHLAN; BROWN, 2006). Nevertheless, for any long-term monitoring the sampling period x processing time of samples should be considered. In an ideal scenario, the sampling scheme should be monthly or fortnightly for at least a year since the combination of benthic life style and short life cycle, which can be of less than 15 days in some cases, leads the meiofauna to respond extremely fast to any possible environmental disturbances (SILVA et al., 1997). Therefore, using short sampling intervals would provide a more reliable seasonal variability of the meiofauna. But perhaps applying this sampling scheme would provide such a large number of samples by the end of the project as to make this strategy impracticable because the sampling process is so time-consuming. Thus, it is suggested that the sampling design should include at least two or more different seasons, covering both a dry and a wet season, for instance (MARIA et al., 2015).

Although concerns about global warming have dramatically increased, the impact of climate change on the meiofauna is still very little understood worldwide; only two studies having been undertaken on sandy beaches (see VANAVERBEKE et al., 2009; GINGOLD et al., 2013). In Brazil, the most closely related studies that could be used as elements for the understanding of climate change are those that analyze the natural life cycle of the meiofauna over an one-year period (e. g., ESTEVES et al., 2003; 2004; MARIA et al., 2008a; VENEKEY et al., 2011). However, these studies address the question to a single nematode population indicating that certain species increase their density during rainy or dry seasons.

Based on the results presented here, it can be seen that there are few long-term studies focusing on the meiofauna community (two out of six one-year studies), it is, therefore, still very premature to draw any conclusion concerning the relationship between climate change and the actual meiofauna distribution, diversity and density on Brazilian sandy beaches.

There is a lot of discussion concerning the use of the meiofauna community to understand the effect of climate change. An environmental impact assessment has shown that each meiofauna organism possesses distinct responses to the same kind of impact (MIRTO et al., 2012). We cannot, therefore, recommend that the assessment of the meiofauna community as a whole be used in this kind of study. Another negative aspect is related to the identification of the meiofauna organisms that requires the involvement of various experts. It is also time consuming since the observation of specific characters of tiny organisms calls for very laborious and careful observation always under the light microscope. A possible solution that may overcome these negative aspects is the choice of the most dominant group of the meiofauna to work in long-term monitoring programs or even to choose a very abundant species and follow its population structure.

Another important aspect for a very successful monitoring program is the standardization of the meiofauna sampling methodology in order to make the data comparable among geographical regions of the country. Brazil is a country of continental dimensions and it is to be expected that the effect of climate change should be distinct in each geographic area. Long-term monitoring is a valuable tool for understanding of the dynamic changes of the meiofauna as well as giving a better picture of the local biodiversity that can be compared with further scenarios of climate change.

In addition to a long-term monitoring program of the meiofauna in different geographical regions of the country, some simple laboratory and/or *in situ* experiments would be a worthwhile strategy. Some simple questions related to climate change could be raised and easily answered by means of experiments. We can give some examples: (1) What is the impact of sea level rise on the intertidal meiofauna community? (2) What is the behavior of the meiofauna community under high temperatures? (3) Can intense rainfall wash meiofauna into deeper sediment layers? There are already two successful approaches that predict the response of meiofauna under those changed climatic conditions (VANAVERBEKE et al., 2009; GINGOLD et al., 2013). In the former study it is shown that artificial rain can change the nematode community of European beaches, but the degree of change depends on the dynamic of the ecosystems, microtidal beaches being more affected than macrotidal ones. The latter study analyzed the influence of high temperatures on the nematode community and a loss of predator and omnivorous nematodes - important for the top-down control of the community, consequently leading to a change in the whole interstitial food web - was observed. Although results of experiments should be interpreted with caution since they are an oversimplification of what happens in the field, they can be a valuable tool to answer specific questions.

Our results show that the meiofauna assessments undertaken on Brazilian sandy beaches are unevenly distributed among the various geographical regions of the country thus making it very difficult to arrive at any conclusive statement concerning the influence of climate change on what is currently known of sandy beach meiofauna. We suggest that long term monitoring combined with an experimental approach constitute a valuable strategy to build a complete picture promising some understanding of the impact of climate change on sandy beach meiofaunal organisms.

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Studies on benthic communities of rocky shores on the Brazilian coast and climate change monitoring: status of knowledge and challenges

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Abstract

A rocky shores working group (WG) integrated with ReBentos (Monitoring Network for Coastal Benthic Habitats; Rede de Monitoramento de Habitats Bentônicos Costeiros) was created and linked to the Coastal Zones Sub Network of the Climate Network (MCT; Sub-Rede Zonas Costeiras da Rede Clima) and to the National Institute of Science and Technology for Climate Change (INCT-MC; Instituto Nacional de Ciência e Tecnologia para Mudanças Climáticas), to study the vulnerability of benthic communities on rocky shores and the effects of environmental changes on biomes in such environments along the Brazilian coast. The synthesis presented here was one of the products of this GT, and aimed to collect and review existing knowledge on benthic communities present on rocky shores of the Brazilian coast, their associated biodiversity, and the potential of future studies to accurately predict/measure the effects of climate change on such environments and their biota.

Descriptors: Synthesis, Benthic communities, Rocky shores, Brazilian coast, Climate change.

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Resumo

Um grupo de trabalho de costões rochosos (GT) integrado à ReBentos (Rede de Monitoramento de Habitats Bentônicos Costeiros), e vinculado à Sub-Rede Zonas Costeiras da Rede Clima (MCT) e ao Instituto Nacional de Ciência e Tecnologia para Mudanças Climáticas (INCT-MC), foi criado para estudar a vulnerabilidade das comunidades bentônicas dos costões rochosos e os efeitos das alterações ambientais sobre a respectiva biota. A presente síntese foi um dos produtos desse GT e teve como objetivo principal levantar e revisar o conhecimento existente sobre as comunidades bentônicas de costões rochosos na costa brasileira, a biodiversidade associada, e verificar as potencialidades de estudos futuros para uma previsão/mensuração mais acurada dos efeitos das mudanças climáticas sobre os ambientes e sua biota.

Descritores: Síntese, Comunidade bêntica, Costão rochoso, Costa brasileira, Mudanças climáticas.

INTRODUCTION

Definition and main characteristics of rocky shores

Rocky shores are a transitional ecosystem between land and marine environments, and, together with other benthic coastal habitats, are among the most productive marine environments on the planet. Rocky shores are composed mainly by marine organisms and the biota on the intertidal region, and the challenges is posed by both seawater and air exposures because they are at the boundary between marine and terrestrial environment. Therefore, these organisms and communities are likely indicator systems of the impacts of climate change.

Rocky shores are common intertidal environments in coastal areas throughout the world formed by solid rocks, forming different habitats as steep rocky cliffs, platforms, rock pools and boulder fields. In the Brazilian coast, there are two different rocky shore formations. The first are true rocky shores formed by rock structures extending from the ocean floor to few meters above sea level, which are mostly found in the southeast and on islands. The second, in the north and northeast regions, are clusters of rock fragments formed by boulder that may hold species characteristic of rocky shores (GUILARDI et al., 2008).

Rocky shores are dynamic environments under the influence of a wide variety of biotic and abiotic drivers. As a result, a high richness of species of ecological and economic importance, such as mussels, oysters, crustaceans and a diversity of algae and associated fish (LITTLER; LITTLER, 2000) develop in this environment. A high biomass and primary production of microphytobenthons and macroalgae is found due to the input of large quantities of nutrients from terrestrial systems. Consequently, rocky shores are feeding, growth and reproduction sites for many species of consumers (COUTINHO; ZALMON, 2009). The great diversity of species on rocky shores and the availability of substrate as a fundamental resource for sessile organisms increases biological interactions, the strength of which is mediated by environmental factors (ex. hydrodynamics, temperature, tides, etc.) (GUILARDI et al., 2008).

The integration of the environmental drivers (wave exposure, emersion time) and the biological interactions (e.g. competition, predation) influences the pattern of distribution of organisms at small spatial scales. As a result, organisms are distributed at different vertical levels according to their tolerance to dissecation and dominance ranges, establishing worldwide zonation patterns (STEPHENSON; STEPHENSON, 1949).

In the Brazilian coast, an overall pattern of distribution and dominance of organisms is found with some regional differences depending on local characteristics. In general, the infralitoral fringe (zone between the lowest tide during spring and neap phases) is dominated by a wide variety of macroalgae with presence of Sabelariid reefs of the genus *Phragmatopoma* spp, mussels *Perna perna* and barnacles *Megabalanus coccopoma*, while the midlitoral zone (between the lowest neap tide and the high tide level) is dominated by the barnacles *Tetraclita stalactifera* (at low midlitoral) and *Chthamalus bisinuatus* (at high midlitoral), mussels *Brachidontes* spp and biofilm. Consumers are found over these zones in different dominance mainly by limpets (infralitoral fringe and midlitoral), periwinkles (supralitoral), whelks and sea urchins (infralitoral fringe) (see COUTINHO; ZALMON, 2009; CHRISTOFOLETTI et al., 2010, 2011a,b).

The dominant organisms in this region are functionally similar around the world, which facilitates the standardization of initiatives monitoring in different parts of the world. Secondary effects of global climatic changes such as increases in water and air temperature, sea level variations and reduction in water pH may also affect the diversity, distribution and abundance of rocky shore organisms. Increases in temperature and sea level and the reduction of water pH are examples of global changes that may lead to substantial changes in the diversity, distribution and abundance of species on rocky shores. Understanding such shifts depends on an intense and sustained effort of ecological monitoring combined with field and laboratory experiments.

In the intertidal, the organisms are subject to air exposure once or twice a day at low tide due to the diurnal or semi-diurnal tidal regime. Periods of spring tides are the most critical for these organisms as the time of exposure reaches the maximum. In this moment, organisms may face temperatures above 50° C and endure a temperature range of 30° C in a single day depending on the water temperature at high tide (as observed in Arraial do Cabo, RJ), the season, latitude, time of day, low tide, and where the organisms are located. Therefore, many resident organisms are considered to be at their physiological tolerance limit, and any changes in abiotic parameters related to climate change, such as water or air temperature, or the air exposure time, may lead to negative events such as mortality or even local extinction (HELMUTH, 2002, 2009).

To study the vulnerability of benthic communities on rocky shores, and the effects of environmental changes on biomes in such environments along the Brazilian coast, a rocky shores working group (WG) integrated with ReBentos (Monitoring Network for Coastal Benthic Habitats; Rede de Monitoramento de Habitats Bentônicos Costeiros), was created and linked to the Coastal Zones Subnetwork of the Climate Network(MCT; Sub-Rede Zonas Costeiras da Rede Clima), and to the National Institute of Science and Technology for Climate Change (INCT-MC; Instituto Nacional de Ciência e Tecnologia para Mudanças Climáticas). The WG aimed to consolidate a research network, through an extensive methodological discussion among researchers from different regions of the country, and began a time series to obtain standardized data that enable continued monitoring of these environments.

Thus, the main goal of this study is to collect and review existing knowledge on benthic communities present on rocky shores, their biodiversity, and the potential of future studies to accurately predict/measure the effects of climate change on such environments and their biota. The study was divided into three main parts: 1) Environment, comprising definition and main features, location along the coast, ecosystem/environmental services rendered and the main local threats; 2) Survey of the existing knowledge; and 3) Effects of climatic changes.

Geographical distribution of habitat on the coast

Diversity on rocky shores throughout the Brazilian coast is the result of a complex interaction between biogeographic and historical factors. Such factors include the characteristics of the water bodies (particularly of the Northern and Southern currents of Brazil), of the Falkland currents, and of the outcrops located in the South Atlantic Central Water (SACW); hard substrate availability and the presence of large freshwater systems and biotic interactions. OLIVEIRA (1998) demonstrates that the Amazon and La Plata Rivers are the primary determining factors of the phycofloristic features of our coast. These two large rivers function as insurmountable barriers for many species of benthic marine organisms due to the high volume of fresh water and sediment supplied to the marine environment (OLIVEIRA, 1998). Apparently, some species abundant in the Caribbean and absent from Brazil have reached the Caribbean from the Indo-Pacific, whereas the Amazon River already drains a considerable amount of water into the Atlantic. This pattern would generally explain the biogeographical differences between the marine biota along the northeast coast of Brazil and that of Venezuela and Colombia. Nevertheless, it is not clear what possible influence (or not) the African coast may have on the composition of Brazilian flora and fauna. Some of the common species observed in both coast may be related to the age of the barriers, the actual currents that reach the northeastern coast from Bengala Currents, or transportation by ships which seems to be the case of Mitilidae *Perna perna*, which is abundant in the Brazilian southeastern coast and South African coast, and apparently arrived came by ships slaves (FERNANDES et al., 2008).

At the southern end, the La Plata River plays the same biogeographical role by blocking species of temperate affinity, which occur on the Argentine coast, from invading (at least seasonally) the southern and southeastern coast of Brazil.

We can divide the Brazilian coastal zone into three main areas concerning the presence of rocky shores based on the distribution of benthic organisms:

1. One zone ranges from Amapá to the north of Bahia, and is characterized by a coast of unconsolidated sediment or hard sediment, formed mainly of sandstone reef ecosystems, and encrusted by coralline algae, sponges, corals, bryozoans and several other groups of benthic invertebrates. The reef ecosystem occur mainly from the coast of Rio Grande do Norte state until the mouth of the São Francisco River (southern Alagoas border), extending approximately 600 km. The reef ecosystems are composed of coral or biogenic reefs, and of sandstone reefs located in the offshore zone and near the coastline, where the upper reef platform is exposed during low tide and with benthic organisms typical of intertidal regions. The small rock formation present near Cabo de Santo Agostinho (Cape of Saint Augustine; Pernambuco coast), and other rocky formations along the north and northeast coast, formed mainly by boulders (some large) are exceptions.
2. This zone comprises the coastal area from north of Bahia, where crystalline outcrops forming rocky shores are common, to the south of the island of Santa Catarina, characterized by large bedrock availability on the continental edge, and cut by numerous bays and coves, as well as in small beaches separated by rocky spurs, and numerous islands and islets. The deep-water upwelling arising from the SACW occurs within this zone. The main point of upwelling occurs in the region of Cabo Frio (RJ) (CARBONEL, 2003).

The last region extends from the southern area of Santa Catarina to the Torres region (RS), and is characterized by extensive sandy beaches, and rare crystalline outcrops on the mainland and islands.

In addition, we find oceanic islands such as Fernando de Noronha, São Pedro and São Paulo, Trindade and Martim Vaz, that also present extensive rocky shores.

In this biogegraphical context, the most extensive rocky shores are present, almost exclusively, on the southern and southeastern coast of Brazil. The main characteristic of the Southeast is the proximity of Serra do Mar, which in many places directly reaches the sea. The sudden inflexion of the orientation of the coast, and of the isobathymetric to the west (near Cabo Frio), due to the Rio de Janeiro fracture zone caused the structural alignments of the crystalline basement (northeast-southwest direction), to become shortened by the approximately east-west orientation of the coast between Cabo Frio and the Bay of Angra dos Reis. Thus, we can consider that the main stretch of the Brazilian coast with rocky shores ranges from Espírito Santo to Torres, the last hard natural substrate in the state of Rio Grande do Sul. The species composition has subtropical characteristics, and a high diversity of species in this region, except for the area influenced by the Cabo Frio upwelling. The benthic fauna and flora of the area influenced by the Cabo Frio upwelling has elements with temperate and tropical affinities. This region acts as a biogeographical barrier for a large number of species.

Survey of existing knowledge

A total of 327 scientific papers from 1944 to 2014 were used to synthesize studies on rocky shores along the Brazilian coast (Figure 1 and Appendix 1: http://www.io.usp.br/index.php/arquivos/send/337-vol-64-special-issue-2-2016/3992-annex-1015). These studies were grouped into articles published in journals, thesis or dissertations, books or chapters, and proceedings. In this survey, reef ecosystems were also counted for a separate summary work because in many situations, these ecosystems are located neighboring rocky shores. In addition, it was also important to compare rocky shore ecosystems with reef ecosystems to assess the research efforts already undertaken in these ecosystems.

The studies conducted from 2000 to 2014 were classified by type of study defined as follow (Figure 2):

Biodiversity – studies on more than one floral or faunal species, or on a group of organisms.

Observational – descriptive studies emphasizing ecological aspects.

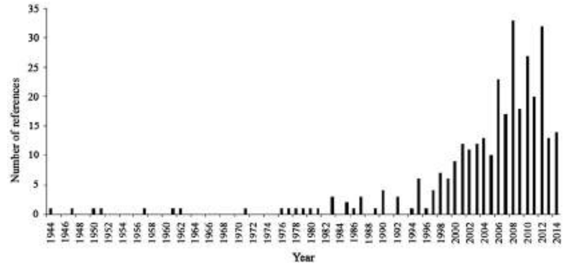

Figure 1. Number of references on rocky shores and coral reef ecosystems, per year.

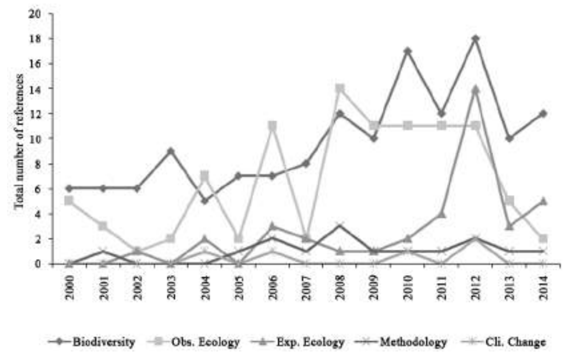

Figure 2. Total number of references on benthic communities per type of study, from 2000 to 2014.

Experimental – studies that involve some type of sample or experimental design in the field or controlled laboratory conditions, used to answer questions or test scientific hypotheses.

Methodological – Studies with emphasis on the establishment of field sampling or experimental methods.

Climate changes: Studies relating climatic aspects to benthic organisms.

Although they began in the 40s, studies on rocky shores in Brazil experienced a boost in the 80s (Figure 1), mainly including floral and faunal surveys. A high variability in the number of observational ecological studies over time, and an increase in the number of experimental ecological studies from the year 2010 are apparent. It is also important to note that biodiversity, observational, and (recently) experimental studies have prevailed on the Brazilian coast. Studies related to climate change have been minimal, showing the urgent need to implement this type of study (Figure 2).

The substrate type used was also identified in the survey. A good portion of the studies focused on rocky shores and coral reefs. However, studies on sandstone reefs and boulders were observed in locations such as northern and northeastern Brazil, where true "rocky shores" are virtually inexistent (Figure 3).

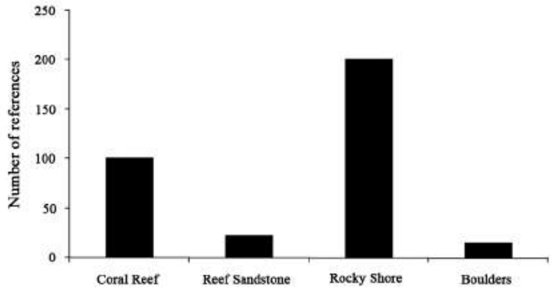

Figure 3. Number of references on rocky shores and reef ecosystems from 1944 to 2014 grouped by type of substrate.

The survey also showed that much of the information available in the literature is located in scientific papers (Figure 4). However, nearly 20% of the studies available are thesis, dissertations and conference proceedings. This percentage is likely to increase over the coming years due to the adoption of extended abstracts by national conferences of the field such as the Brazilian Congress of Zoology (Congresso Brasileiro de Zoologia), Brazilian Congress of Oceanography (Congresso Brasileiro de Oceanografia) and Brazilian Congress of Marine Biology (Congresso Brasileiro de Biologia Marinha).

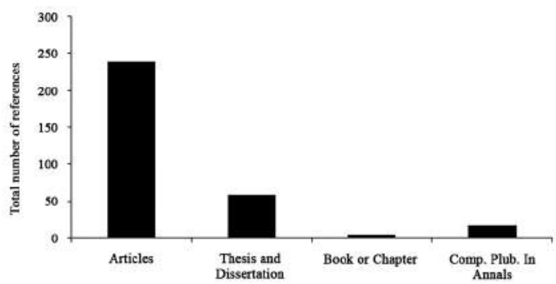

Figure 4. Number of references on rocky shores and reef ecosystems, per type of publication.

Most studies on rocky shores in Brazil were concentrated in the southeast, which may be explained by the larger number of rocky shores in this region, and by the existence of more researchers in Rio and São Paulo (Figure 5). We may also observe a large number of studies in the State of Bahia due to the Abrolhos Park, which has been the target of numerous studies carried out by Brazilian and foreign scientists.

Main local threats beyond the climatic changes

The exploitation of species of economic interest, the introduction of exotic species, waste, land speculation, pollution and over fishing are prominent among the

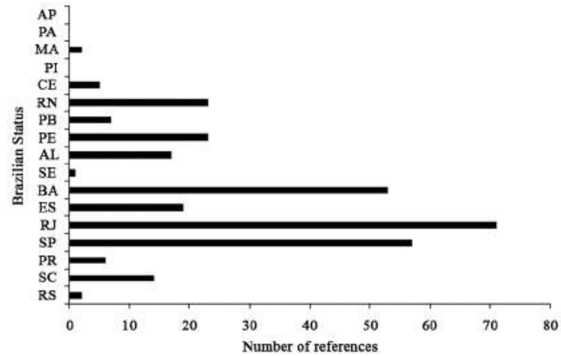

Figure 5. Number of references on rocky shores and reef ecosystems per Brazilian state.

factors that exert pressure on the biological diversity of rocky shores.

The mussel *Perna perna* Linnaeus, 1758, is one of the main sessile species captured on the rocky shores of the southeastern region of the Brazilian coast, and can be collected at a young age to be used as seed for aquaculture systems, or as adults for food. The effect of intensive mussel extraction has not been evaluated, however it certainly changes the entire community structure in places where mussels are dominant. Fauna associated with the mussel are also simultaneously removed, changing the structure of those communities and of other benthic organisms.

The introduction of some exotic species, whether voluntary or controlled (such as the oyster *Crassostea gigas* Thumberg, 1793), may benefit the local economy. The oyster, introduced in the 70s for cultivation in Arraial do Cabo, RJ, does not yet have a record of breeding under natural conditions in the region, as a certain threshold of low temperature is required for gonad maturation. The oyster is currently widely cultivated on the coast of Santa Catarina and has a great economic importance for the region. On the other hand, the arrival of exotic species from the hulls of ships, oil platforms and other floating artificial structures are serious problems for the native fauna. The most recent case has been the spread of sun corals (species *Tubastrea coccinea* and *T. taguesensis*) on the Brazilian coast (CREED et al., 2008). This organism grows significantly in artificial and rocky substrates in the southeast, especially in the region of Ilha Grande, RJ, and it poses a potential risk to the local community biodiversity. Alternative measures to control sun coral are needed to contain the coral in other areas of the Brazilian coast, as there are already records of this species on the northeast (BA, AL) and southeast (SP, PR and SC) coasts (COUTINHO et al., 2013).

Garbage on the rocky shores may compromise population development, especially in the intertidal zone because garbage, among other potential impacts, may reduce water circulation and create shade for algae. However, the mentioned effects require evaluations to be replicated at broad temporal and spatial scales.

Building of ports, buildings, factories, and real estate expansion in regions near urban areas, are the main anthropogenic pressures on rocky shores. The building of houses, among others, due to privatization of rocky shores is a major problem for the organisms of this ecosystem. The insertion of areas with artificial hard substrate from large construction projects on the north coast of the state of Rio de Janeiro (e.g., Açu port) has been observed, creating a link where previously there was no hard substrate. In addition, the release of, often in natura, sewage impairs the growth of many benthic species.

Pollution from industrial effluent may lead to a reduction of species or even change the reproductive processes of benthic organisms. For example, the presence of heavy metals, TBT, and other compounds may directly affect the ratio of males and females in gastropod populations, causing changes in the reproductive organs called imposex. Populations of gastropod predators inhabiting rocky shores near port regions, such as *Thais* (=*Stramonita*) and *Leucozonia*, exhibit the imposex process, generating a much higher proportion of males over females due to the presence of TBT in the water (LIMAVERDE et al., 2007)

Overfishing carried out by diving in the subtidal region of rocky shores is one of the main environmental impacts affecting the structure of benthic populations. The removal of top predators in the food chain can increase the abundance of herbivorous fish, reducing algal coverage. Rocky shores are used by fishing and extractivist communities, which rely on them for survival in sparsely populated regions, where these ecosystems service the communities.

Tourism and increases in coastal area population (whether for housing or vacation) have intensified problems in the southeast. The privatization of beaches to build condominiums, for example, has become more severe in the past years, especially in the southeast, despite being illegal in the Brazilian constitution. Such condominiums lead to several environmental issues that will contribute to the degradation of rocky shore ecosystems. In addition, recreational tourism using motorboats directly affects the communities present on rocky shores with oil spills and docking in reef areas.

Rocky shores, in turn, do not have a legally defined status for public recognition as a proper or defined ecosystem when compared to other environments such as reefs or mangroves. Consequently, public policies established for the preservation of rocky shores are defined within a broader context of other ecosystems, and thus, such shores lack their own identity. Therefore, there is little awareness, regarding the different impacts that rocky shores are subject, to making them hostage to unplanned development. Rio das Ostras, RJ, where a municipal law establishes protection of rocky shores in the county (known as Natural Monument of Rocky Shores), is an exception to the rule.

In this context, rocky shores are essential ecosystems for conservation and to decrease the vulnerability of coastal regions. The potential effect of biodiversity loss, as the species of ecological and economical importance, on ecosystem functioning and the services provided to society is troubling. It is important to consider how significantly rocky shore biodiversity can help in maintaining the stability of coastal ecosystems. Natural systems considered stable are more reliable at providing environmental services.

Scenarios of the expected climatic changes indicate an increase in physical stress (e.g., storms). Local anthropogenic impacts resulting from the multiple uses of coastal regions may cause the loss of some key species in ecosystems. It is unclear how these different impacts may affect ecosystem processes and, consequently, environmental services.

Effects of climate change on rocky shores and their biodiversity

Increases in surface water temperature and sea level, changes in salinity and in hydrodynamics related to exposure to waves, undertow and ocean circulation are among the impacts of global climate change predicted for marine ecosystems. Furthermore, a decrease in seawater pH is expected because of the increased CO_2 concentration in the atmosphere (NICHOLLS et al., 2007). Little has been produced on climate change research in Brazil, but understanding the knowledge from other areas in the world, and the start of a monitoring approach in the Brazilian coast will help to better understand the vulnerability and the impacts for this region.

Coastal ecosystems are among the most vulnerable to the changes caused by climate change, especially the intertidal areas, which have shown faster biogeographic changes (BARRY et al., 1995; HELMUTH et al., 2006) than those found in terrestrial environments (ROOT et al., 2003). Long-term monitoring studies have shown that the distribution limits of the intertidal biota of hard substrates have progressed toward the poles at a rate of over 50 km per decade (RICKETS, 1985; SOUTHWARD et al., 1995; HELMUTH et al., 2006), and highlight how this action is urgent in a large and diverse coast as found in Brazil.

Invertebrates and seaweeds, inhabiting intertidal habitats may, be particularly vulnerable to fluctuating temperatures, as individuals must adapt to the extreme temperatures of both the terrestrial and marine environments (FIELDS et al., 1993). A range of thermal conditions are found at small spatial scales in the intertidal zone, and they may exceed the range of large latitudinal bands. Therefore, the inhabiting organisms are believed to be at the limit of their physiological tolerance and any changes in abiotic parameters (e.g., temperature and air exposure time) could lead to death, local extinction (HELMUTH, 1999; HELMUTH, 2002; MASSA et al., 2009) or to the expansion of the range and distribution area. Thus, intertidal areas are potential environments to assess the effects of climate change (HELMUTH, 2009). In this context, it is important to consider that rocky shores in the Brazilian coast go from tropical zone to subtropics, thus, changes in temperature can lead to a changes in the range of distribution for many species in these boundaries. For instance, increasing in temperature can expand the southern limit of many species from the region of SP/PR/SC towards the south.

The passage of cold fronts is a natural and unpredictable weather disturbance, where the associated winds generate high-energy waves able to disturb benthic communities, and play an important role in structuring local communities. The south and southeast coast in Brazil are particularly affected by the influence of cold fronts from the South, where the dynamics of oceano-climatic processes and the benthic-pelagic links are influenced at different temporal scales (MAZZUCO et al., 2015). These extreme events may arise as a result of climate change, affecting the structure and functioning of benthic communities of the intertidal zone. The influence of waves/undertow/storms on rocky shores has been addressed considering changes in community species composition, species richness and diversity, the intensity of interactions such as competition and predation, and even the expansion of the zone occupied by organisms, and the respective bands. Such changes are reflected in the "patch" dynamics of organisms (see review in COUTINHO; ZALMON, 2009). Studies seeking to understand the effects of climate-mediated disturbances (e.g., storms and weather fronts) on benthic assemblages at temporal and regional scales and in coastal areas have been conducted worldwide (POSEY et al., 1996; UNDERWOOD, 1999; WILLIAMS; ROSE, 2001; AAGAARD et al., 2005; HOUSER; GREENWOOD, 2007). However, the consequences of climate change in the mid-medium and long term on community structure should be carefully evaluated given the scarcity of large time series data on the Brazilian coast.

Local monitoring is required to determine the factors that definitively influence the occurrence of each organism (DENNY et al., 2004), as differences are often not explained in terms of absolute data. Air temperature, for example, is not the temperature experienced by organisms on the rocky shore, which is formed by several components that often are not considered in the final analysis of the measured temperature. These organisms are doubly subject to possible climate change for being exposed to two environment fluctuations, terrestrial and marine. Increased rain frequency changes salinity, adversely affecting the traits of different groups such as mortality rate, release of larvae, and others (SIMPSON; HURLBERT, 1998; CHAN et al., 2001; BRAVO, 2003; RESGALLA et al., 2007). The combination of factors must also be considered. An organism may adapt to an environmental variation when exposed to only one. If more than one factor is modified (e.g., salinity and pH), the physiological pressure may be intolerable for the organism (PRZESLAWSKI et al., 2005; VERWEEN et al., 2007; RESGALLA JUNIOR et al., 2007).

Long-term time series are important for understanding the functioning of this ecosystem, an environment that undergoes natural seasonal community changes, with some sessile organisms expanding or retracting their occupation in the bands and other organisms appearing at a certain time of year covering the entire range or completely disappearing at a different time (e.g., several species of the genus Ulva). Long-term time series help to assess how natural oceanographic events, such as the North Atlantic Oscillation (NAO), and more specifically to the southern hemisphere, the El Niño Southern Oscillation (ENSO), affect species distribution gradients. Time series analysis (wavelet) showed that relationships between recruitment and environmental indexes are more consistent annually, but multi-year periodicity is also important (MENGE et al. 2011). Thus, conducting studies that link large-scale measurements to local scale measurements is important to compare and predict changes resulting from human activity.

In summary, global changes comprise complex changes. However, these complex changes have direct indicators such as air and sea temperature, oxygen availability, salinity and pH, abiotic variables that greatly influence the biology of all species. Physiological stresses resulting from changes in the afore mentioned variables and from extreme events such as cold fronts/undertow may cause large biogeographical changes and affect the habitat distribution mosaic (SOMERO, 2012).

Despite the wide coastline and the presence of different climate regions that are potentially influenced by climate change effects, these effects on rocky shore communities are still poorly studied in Brazil. Initiating studies that address this topic is urgent. The simplified protocol developed by the rocky shores of ReBentos WG (COUTINHO et al., 2015) aims to encourage the engagement of groups working in this environment to obtain long-term time series on community changes. In addition, organism-level studies are critical to understanding the ability to adapt to climate change.

Finally, testing scientific hypotheses is important to facilitate the unification of studies related to monitoring the influence of climate change on rocky shores; for example, i) if hydrodynamics and average sea level variations will induce changes in the zonation pattern (such as, changing organism colonization sites in regards to the current locations, or enlargement/reduction of dominance bands); ii) if changes in undertow frequency and intensity will promote more frequent physical disorder in benthic ecosystems, and cause the pulling out and/or fragmentation of organisms (especially in the intertidal area), shifting species composition and abundance; iii) if changes in precipitation will change the input of freshwater and sediment into the sea, and the evaporation rate, which in turn will affect variables such as salinity and sea water transparency, creating unfavorable conditions for stenobiont species, and inducing changes in species composition and abundance; and iv) if changes in temperature and sea water acidification, will influence the metabolism of sessile organisms (especially the perennial), affecting growth, reproduction and survival rate, and inducing shifts in species composition and abundance.

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ReBentos

Climate changes in mangrove forests and salt marshes

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Abstract

This synthesis is framed within the scope of the Brazilian Benthic Coastal Habitat Monitoring Network (ReBentos WG 4: Mangroves and Salt Marshes), focusing on papers that examine biodiversity-climate interactions as well as human-induced factors including those that decrease systemic resilience. The goal is to assess difficulties related to the detection of climate and early warning signals from monitoring data. We also explored ways to circumvent some of the obstacles identified. Exposure and sensitivity of mangrove and salt marsh species and ecosystems make them extremely vulnerable to environmental impacts and potential indicators of sea level and climate-driven environmental change. However, the interpretation of shifts in mangroves and salt marsh species and systemic attributes must be scrutinized considering local and setting-level energy signature changes; including disturbance regime and local stressors, since these vary widely on a regional scale. The potential for adaptation and survival in response to climate change depends, in addition to the

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Resumo

Esta é uma síntese enquadrada na Rede de Monitoramento de Habitats Bentônicos Costeiros (ReBentos, GT4: Manguezais e Marismas), embasada em literatura científica que examina interações entre clima e biodiversidade, assim como fatores antrópicos, incluindo aqueles responsáveis pela diminuição da resiliência sistêmica. O objetivo deste trabalho é determinar as dificuldades quanto à detecção de sinais precoces e alertas de mudanças climáticas com dados de monitoramento. No presente trabalho, também foram exploradas formas de contornar os diversos obstáculos identificados. A exposição e a sensitividade de espécies de mangue e de marisma, bem como dos ecossistemas dos quais fazem parte, os tornam extremamente vulneráveis e potenciais indicadores ambientais de mudanças de nível do mar e outras respostas às variações do clima. Entretanto, a interpretação de mudanças em manguezais e marismas e em seus atributos sistêmicos deve ser meticulosa, considerando assinatura energética, regime de distúrbios e pressões ambientais em cada local de estudo. Os potenciais de adaptação e de sobrevivência, em resposta a tais mudanças, dependem da fisiologia de cada espécie e dos processos coninherent properties of species, on contextual processes at the local, landscape, and regional levels that support resilience. Regardless of stressor type, because of the convergence of social and ecological processes, coastal zones should be targeted for anticipatory action to reduce risks and to integrate these ecosystems into adaptation strategies. Management must be grounded on proactive mitigation and collaborative action based on long-term ecosystem-based studies and well-designed monitoring programs that can 1) provide real-time early warning and 2) close the gap between simple correlations that provide weak inferences and process-based approaches that can yield increasingly reliable attribution and improved levels of anticipation.

Descriptors: Biological indicators, Climate changes, Mangroves, Salt marshes, Sea level rise, Brazil.

textuais onde reside a resiliência e a capacidade de persistir (em níveis local, de paisagem e regionais). A zona costeira deve ser alvo de medidas antecipatórias para redução de riscos por quaisquer impactos, uma vez que nela há intensa convergência de processos sociais e ecológicos. Os ecossistemas dessa zona devem ser integrados em estratégias de adaptação. O manejo costeiro deve ser embasado em mitigação pró-ativa e colaborativa de longo-termo, sempre com base em estudos ecossistêmicos e em programas de monitoramento que possam 1) prover sistema de alerta precoce; 2) preencher lacunas entre correlações simplistas que proveem inferências fracas, e abordagens baseadas em processos que levem a atribuições mais confiáveis e a melhores níveis de antecipação.

Descritores: Aumento do nível médio relativo do mar, Indicadores biológicos, Manguezal, Marisma, Mudanças climáticas, Brasil.

INTRODUCTION

This synthesis is framed within the scope of the Brazilian Benthic Coastal Habitat Monitoring Network (ReBentos WG 4: Mangroves and Salt Marshes) assessment. It presents the results of a survey of the Brazilian and relevant scientific literature regarding mangrove and salt marsh ecosystem biodiversity, focusing on publications that examined species-climate interactions as well as responses to human-induced stressors. A goal of the synthesis is to identify attributes, obstacles and barriers related to the detection of climate signals from monitoring data that could facilitate or hinder the prediction of climate change impacts on species, habitats and coastal landscapes. The assessment attempts to provide a foundation for a more accurate perspective for interpreting change. Along these lines we also explore ways to circumvent some of the difficulties and gaps identified. Most climate changes are expected to be subtle and difficult to detect, but pervasive and highly consequential for coastal species that are tightly coupled to both atmospheric and oceanographic processes. Climate change is expected to accelerate and take place at a rate that may be faster than the speed of species and system adaptation; the identification of vulnerabilities and factors that increase or erode resilience is relevant for conservation planning and management in the context of climate change. Most of these coastal systems are highly productive, capturing large amounts of carbon from the atmosphere while simultaneously local hydrodynamic and geomorphic forces provide effective means for burial, sequestering carbon *in situ*, or exporting carbon offshore, where it enters the marine portion of the carbon cycle and storage in deep-water sediments. Thus, these ecosystems offer opportunities for integration into climate adaptation strategies for wetlands which, despite constituting about 5 to 8% of the terrestrial landscape, sequester and store carbon at the rate of 118 g C/m^2/yr (MITSCH et al., 2012).

Actually only a very small amount of the planet's active carbon resides in the atmosphere, much of it is stored in wetlands. The sequestration process in wetlands is self-organized and self-sustaining as long as substrates remain anaerobic, but has remained underestimated and poorly recognized as an ecosystem service for regulating and stabilizing atmospheric CO_2 (AUSTRALIAN GOVERNMENT, 2012). The sequestration capacity of these systems is significant in two critical ways; first, they capture and, second, they provide for the long-term storage of carbon. The destruction, degradation or conversion of these areas can release large amounts of carbon stored since these systems began to occupy transgressive terrains some 6,000 yrs ago (NATIONAL RESEARCH COUNCIL, 1990). This implies that these areas have potential for management to offset industrial and country-level greenhouse-gas emissions and, specifically for Brazil, its Intended Nationally Determined Contribution (INDC) that has been considered inconsistent with limiting warming to below 2^{o}C (CLIMATE ACTION TRACKER, 2015). Degradation of coastal wetlands would hinder Brazil from meeting its INDC targets under current policies and would require more stringent emission reductions to reach the desired emission reduction goal. Actively protecting these areas for carbon sequestration would make INDC goals easier to reach. Coastal wetlands due to the proximity to the sea are vulnerable to negative climate impacts derived from terrestrial/atmospheric and oceanic climate driven processes (such as increased sea level, storminess and increased wave scouring and coastal erosion) but these losses are exacerbated by poor land use practices. In Brazil these systems are exposed to extremely destructive non-climatic factors, including reclamation for large-scale harbor development and mariculture (shrimp farming), salt harvesting as well as urban sprawl, triggering a coastal squeeze that erodes the capacity for systems to accommodate to rising sea level and to adapt and persist. The ultimate objective of the United Nations Framework Climate Change Convention (1992 UNFCC) is to reduce local emissions in a manner that would allow ecosystems to adapt naturally to climate change (Article 2). In this sense the coastal landscapes we surveyed are indeed "Working Landscapes"; areas to be managed for the protection of human-ecological linkages as well as the sustained delivery of ecological services to the nation and to the global community.

Mangroves and salt marshes

Mangrove and salt marsh species are facultative halophytes with special adaptations to the muddy anaerobic and saline environments they occupy. These are evolutionary responses to the conditions typical of these habitats; such as prolonged waterlogging, anaerobicity and salinity as well as reproductive, dispersal and growth properties that allow rapid colonization of geologically ephemeral substrates. Coastal wetlands grow and decline in response to a number of geomorphic, hydrologic, climatic and human-induced stressors, directly or coincidentally associated with sea-level change (PHILLIPS, 1999). Changes in structural development and in species distribution can generally be correlated with alterations to the tidal and salinity regime or alterations in hydrology (fresh water inputs including seepage and runoff) or alterations in substrate elevation and granulometric composition (SCHAEFFER-NOVELLI et al., 1990, 2002; CUNHA-LIGNON et al., 2011; CHARLIER-SARUBO et al., 2015; SORIANO-SIERRA et al., 2015; PINHEIRO; ALMEIDA, 2015). Fresh water-dominated environments inevitably exclude mangrove plants due to the superior adaptation of freshwater plants (glycophytes) to environments where salt is not limiting.

Mangroves

Mangroves present discontinuous distribution along the Brazilian coast, covering an area of 9,600 km^2 which represents the third largest mangrove area worldwide in a single country (GIRI et al., 2011). According to SPALDING et al. (2010), Brazilian mangroves hold the second place globally, occupying a larger estimated area of 13,000 km^2. These values correspond to about 7-8.5% of the global mangrove area in the world (FAO, 2007; SPALDING et al., 2010; GIRI et al., 2011). In Brazil, mangroves occur from Amapá state (04º20' N) to Santa Catarina state (28º30' S) and may present a *continuum* of different features (*facies*), depending on the profile of the coastline and the amplitude of the tides (SCHAEFFER-NOVELLI et al., 1990; SOARES et al., 2012). The plant communities of the mangrove ecosystem are unlike any other terrestrial tropical forest, due to the peculiar environmental conditions in which they become established and the large amount of biomass stored in above ground woody structure, below ground root mass and decayed, but stabilized litter accumulations. Mangrove species are often conspicuously banded forming distinct units (or *facies*) within a mangrove topographic and ecological *continuum*.

The most seaward unit may appear devoid of plant colonization, similar to a bare mudflat exposed during every neap tide, but this can be deceiving because this surface is biologically and geomorphologicaly acting as a platform that captures allopatric resilience in terms of propagules and materials produced by higher level systems. Mud flats are also biologically and trophically active, supporting microbial primary producers and a rich micro and macrobenthic community. The gently sloping mangrove-covered intertidal ramps are formed by fine sediment accumulations that extend from the lowest to the highest reach of the tide. The size of a tidal ramp varies depending on the terrain slope and the tidal amplitude. This geomorphic structure is dynamic and capable of adjusting itself to sea level change driven by local deposition and erosion processes. Rising sea level provides for uninterrupted landward encroachment as long as physical barriers are not present landward. Mangrove establishment and growth provides a positive feedback that promotes increased deposition while roots stabilize and contribute to elevate the substrate diminishing flooding frequency and increasing deposition. Landward encroachment can compensate for temporary loss of outer fringes following episodic events. The outer portion of the tidal ramp is a zone of constant activity in terms of biological and geomorphic processes; sediment deposition and scour, propagule recruitment and short-term change.

Vegetation patterning is driven by the tidal flooding gradient perpendicular to the ramp's long axis and the trajectory and dissipation of the tidal flooding wave front landward. Mangrove stands are dynamic beachheads in a permanent state of aggregation and disaggregation; with the primary control parameter being the tidal energy level and degree of erosional scouring. Mangroves display the attributes of both r and K species which allows the rapid colonization and maturation in relatively unstable substrates. The *apicum* (salt flat), the most landward or elevated feature within a forest is not always present. Its occurrence is associated with less tidal flooding and drier precipitation regimes, being intermittently flooded during spring or the highest and lowest astronomical tides when flooding pumps seawater that becomes subject to intense insolation and evaporation because of the lack of canopy cover. Algal mats prevail here. The macrophytic colonizing vegetation is characterized by herbaceous and shrubby plants. Algal mat assemblages are well adapted to persist under the dominant harsh physical and chemical conditions of the infrequently flooded upper tidal reaches (SCHAEFFER-NOVELLI et al., 2002).

Salt Marsh

Salt marsh ecosystems occupy tropical, subtropical, and higher latitude coastal zones intermittently flooded with seawater. In Brazil, the most extensive salt marshes are located in the State of Rio Grande do Sul, dominated by *Spartina*, *Juncus*, *Paspalum*, *Sesuvium* and *Bacopa*, among others (MARANGONI; COSTA, 2009). Brazil's salt marshes occur all along the sheltered coast, either associated with mangroves or not. The salt marsh flora is adapted to lower temperatures and lower salinities but colonizes similar geomorphic features to mangroves in temperate zones. A sharp ecotone develops when they are found together (CHARLEIR-SARUBO et al., 2015). In transitional climates mangrove-associated salt marshes may form a well-defined fringe of tall grass that facilitates the stranding of propagules that eventually shade and replace the grass species (LEWIS; DUSTAN, 1975; CUNHA-LIGNON et al., 2009). When salt marshes are not associated with mangroves, the entire intertidal muddy platform may become covered by an extensive monoculture of *Spartina*. Associated species, having different tolerance to flooding can form distinct bands; although all must be tolerant of salt water, protracted flooding and an anoxic muddy substrate.

Most typical species of salt marshes are facultative halophytes and some species are intolerant to low salinity values (SORIANO-SIERRA et al., 2015). Salt marsh ecosystems consist mainly of perennial or annual herbs often associated with certain species of low shrub (COSTA; DAVY, 1992). These plants are adapted to saline, waterlogged anoxic substrates, including peat. They show xeric leaves with succulent, thick, and dry-type (thin) morphologies. Their rhizomes have thicker anchoring and delicate absorbing roots, which bind unconsolidated sediments (DAWES, 1998). The root system also releases oxygen into the surrounding substrata, modifying the reducing anaerobic rhizosphere (DAWES, 1998).

The root system is one of the most important structural components of mangrove and salt marsh ecosystems, giving rise to thick and fibrous muds, such as those in areas covered by trees of the genus *Rhizophora* (HESSE, 1961) or grasses of the genus *Spartina* (SORIANO-SIERRA et al., 2015). Roots bind the sediment stabilizing it. This contributes to substrate and soil building and local surface elevation (WELLS; COLEMAN, 1981; HUXMAN et al., 2010). The process of substrate elevation leads to the formation of depositional terraces that can expand seawards or inland tracking rising sea level (ALONGI et al., 2008; GILMAN et al., 2008).

The physiography of salt marshes is shaped by the local hydrodynamics; the interaction between tidal regime, topography and availability and type of sediments (DAWES, 1998) that eventually leads to the development of particular adaptations; each species has a unique tolerance to salinity and frequency of inundation, which produces a distinct zonation in this otherwise low diversity environment. The floristic diversity found in salt marshes shows latitudinal variation, with lower diversity near the Equator (five species) and higher variety in the temperate zone (twenty species). This diversity is temperature dependent but is affected locally by the presence of brackish water gradients that create zonation and banding patterns as a function of salinity and tidal flood duration (DAWES, 1998). Several salt-tolerant plants develop within these salt marshes, mainly on microtopographic rises in the substrate, such as berms along the channels increasing floristic diversity locally (SORIANO-SIERRA et al., 2015). In tropical settings, biological stressors such as intense competition for space and shading results in less structural development and complexity than in the temperate locations where stressors such as excessively high temperature (water and air) are less intense.

Associated fauna

The importance of environmental conditions in determining distribution and abundance of species is a fundamental tenet of ecology (SHELFORD, 1951). Self-organization is the sorting of species after a disturbance that allows a system to reconfigure and continue functioning in a particular state. When allowed to take place unobstructed, self-organization is a major natural subsidy to management, conservation and sustainability.

Besides birds, a high diversity of associated species occupies the different mangrove *facies*. Crabs and other invertebrates are found throughout, but can be more abundant in specific places. The environmental gradients in the mangrove and salt marsh ecosystems produce a multiplicity of different microhabitats and patterns of faunal distribution; horizontal zonation, from the edge of the channel to upland areas, vertical zonation, from the canopy to the ground; and axial zonation, from the estuary mouth to its headwater area as well as temporal variations in abundance (*e.g*., SCHLACHER; WOODRIDGE, 1996; DIELE et al., 2010; DIELE; KOCH, 2010; SCHMIDT et al., 2013).

The tropical mangrove-associated fauna is generally closer to the upper thermal threshold than the temperate salt marsh-associated fauna, which makes them more vulnerable to temperature rise (ALONGI, 2015).

The mangrove crab (*Ucides cordatus*) recruitment occurs mainly close to the lower limit of the *apicum* (SCHMIDT et al., 2009), where conditions allow higher aggregation and better development of juveniles (PINHEIRO; ALMEIDA, 2015). Crabs of this species are distributed spatially to form high densities of small individuals in less flooded mangrove features and sand-rich sediment areas (DIELE, 2000; SCHMIDT et al., 2009, 2013; PINHEIRO; ALMEIDA, 2015). It is expected that the recruitment zone of *U. cordatus* will shift upland with sea level rise. Human occupation at the *apicum* (e.g., by urban development, agriculture, shrimp farming or salt harvesting) is expected to block and prevent this natural displacement and reduce the available space for recruitment (SCHMIDT et al., 2013).

The land crab (*Cardisoma guanhumi*) may also be similarly affected by climate change compounded with direct anthropogenic pressures on its habitat and populations. Studies indicate that recruitment of this species occurs in the *apicum*, with subsequent migration to the contiguous terrestrial vegetation. An opposite migration occurs when the ovigerous females periodically leave adjacent terrestrial vegetation to migrate through the *apicum* until larvae are released into mangrove channels and tidal creeks (GIFFORD, 1962). Therefore, both recruitment and reproduction of *C. guanhumi* depend on the *apicum*, which tends to shrink when blocked by increasing upland development, and increase sea level. Human occupation of the *apicum*, as, for example, by shrimp farming and salt pans, hampers both the migration for larval release and the arrival of recruits, leading the local population of *C. guanhumi* to a more vulnerable stage (SCHMIDT et al., 2013).

Both *C. guanhumi* and *U. cordatus* are potential bioindicators of climate change in Brazilian mangrove forests since their spatial distribution is explained by distinct arboreal mangrove *facies* which would change with sea level rise (NORDHAUS et al., 2006, 2009; SCHMIDT et al., 2008; 2013; WUNDERLICH; PINHEIRO, 2013; PINHEIRO; ALMEIDA, 2015). Due to the complexity of the processes determining the spatial distribution of faunal species, changes in sea level and tidal amplitudes would critically influence mangrove biodiversity.

An increase in the average mean sea level would promote displacement of the zones of occurrence (preferential habitats) of some animal species landward, which is particularly relevant for those species adapted to low flooding frequencies (SCHMIDT et al., 2009).

Variations in sea level can be readily detected based on the vertical displacement of boundaries of sessile invertebrates, such as oysters (VOLETY et al., 2009), that grow attached to the lower structures of mangrove trees, such as aerial roots, prop roots, and branches near the margin of estuarine channels. This correspondence demonstrates the importance of such associated fauna as indicators of sea level variations, as well as indirect forcing influences (BELLA et al., 1992; SKILLETER; WARREN, 2000; SCHAEFFER-NOVELLI et al., 2002; ALFARO, 2010).

Although our exploratory survey of the literature reveals that a fairly extensive body of knowledge regarding mangrove associated fauna exists, naturally this literature has not been framed within the context of climate change. Thus, it is difficult to link population abundances, trends, and expected responses or the identification of specific vulnerabilities, and potential responses to climate change.

Coastal settings; mangrove areas and salt marshes

Considering the dynamics of the different types of coasts that mangroves occupy and their responses to changes in hydrology or tidal levels mangroves are extremely resilient and robust (THOM, 1967, 1984;

KJERFVE et al., 2002; JIMENEZ et al., 1985; BLASCO et al., 1996, SCHAEFFER-NOVELLI et al., 2002; SOARES et al., 2012). Mangrove structure is extremely plastic and may exhibit diverse morphologies and multiple stability regimes (*sensu* SCHEFFER; CARPENTER, 2003), manifested as high or stunted stands, monospecific or mixed forests, and different *geofacies*.

The landward portion is dynamic in regions where seasonal drought is common, where high insolation prevails and rainfall is not evenly distributed. Hypersaline flats fringe mangrove forests in arid environments and die-offs may be common with many dead trees often left standing on the bare flat, or transient forms (successional stages) found when more moist and benign conditions return. When drought is sustained, as during certain interdecadal periods, these areas (*apicum*) may expand and appear "bare" and "unproductive" and even non-mangrove when in fact they represent an alternate mangrove ecosystem state when a longer observational period is adopted, and mangroves reoccupy the space. These areas act as "expansion joints" that allow the system to accommodate to decadal or longer oscillations in climate and tidal period, such as the 18.6 tidal cycle (Metonic cycle) and its interaction with meteorological oscillations (such as ENSO and others) This tidal cycle is reported to trigger the movement of fluid muds and promote accretion that forms mud banks (WELLS; COLEMAN, 1981). This oscillation can coincide with ENSO events that impinge on the Brazilian coast, deepening such effects as drought or greater precipitation. On the positive side deeper saline intrusions can also induce interactions between salinity and sulfide that can influence the recruitment and establishment of mangroves. This tidal cycle is present across the world causing the sea level to drop or to rise at an increased rate, so accounting for it and its interaction with interdecadal climate oscillations (this is crucial for the understanding of *apicum* dynamics, as well as sea level rise detection). Areas of active accretion on the outer edge are characterized by abundant seedlings and juvenile individuals (ALONGI, 2008; ESTRADA et al., 2013; CHARLIER-SARUBO et al., 2015) but the extreme dynamism of this portion of the mangrove belt would make any climate change detection and attribution difficult because change is confounded by increased exposure to short-term atmospheric activity and hydrometeorologcal events such as floods and storminess that drives increased wave and current scouring and tree fall.

According to THOM (1984), mangrove plant species develop in five distinctive geomorphic settings: (I) river-dominated settings; (II) tide-dominated; (III) wave-dominated; (IV) wave and river-dominated, and (V) drowned valleys. The vegetation in these settings is characterized by individual adaptations, tolerances, and requirements associated with such factors as tidal levels, flooding, salinity or edaphic constraints. Local climatic conditions modify the characteristics of a mangrove forest within each setting, imposing limits on colonization, growth, and development (THOM, 1984; WOODROFFE, 1987; SCHAEFFER-NOVELLI et al., 1990; CINTRON-MOLERO; SCHAEFFER-NOVELLI, 1992; VALE, 2010). The most productive and structurally developed mangrove forests (settings I, II and V) are generally those that receive larger subsidies of terrigenous sediment, freshwater supplies and nutrients (THOM, 1984), accumulating large quantities of biomass. Mangrove settings III and IV exhibit intermediate characteristics related to productivity, freshwater inflow, terrigenous sediment, and nutrient input. Thus, structurally well-developed mangrove forests are typically found in active geomorphologic areas, subjected to strong depositional inputs of terrigenous sediments and erosion processes that constantly shift sediments (KJERFVE et al., 2002). These types of environments are dynamic mosaics of habitats, including accretion centers where new vegetation establishes itself, areas of stable growth as well as areas showing scouring, loss of forests and eroding or downgrading substrates (SCHAEFFER-NOVELLI et al., 2002).

Mangrove and salt marsh ecosystems' functions and services facing climate changes

Due to environmental complexity and the time span involved, it is impossible to predict the scope or intensity of changes in the structures that occupy the intertidal zone. Mangrove forests and salt marshes are complex adaptive systems and this entails irreducible uncertainty in their behavior. Uncertainty is irreducible in the sense that it is not decreased by greater knowledge, but must be decreased by prudence, conserving ecological resilience and building propensities for the conservation of the natural processes that sustain self-organization. Maintenance of process is more important than relying on determinism and predictions in conserving living systems (ULANOWICZ, 2009). That is, anticipation and hedging actions are more relevant to planning than prediction when managing complex adaptive systems because of pervasive dynamical instability.

Ecosystems are always in flux, populations fluctuate naturally and resilience varies through time. The structure of an ecosystem, including its different physiognomies, is controlled largely by inter- and intraspecific competition and selection of propagules (SHELFORD, 1951), with chemical and physical factors showing less direct importance, since the system and its species creates microclimates that dampen or ameliorate stressors. However, ecosystem persistence requires change; it is only through constant probing of its stability domain (*sensu* HOLLING, 1973) that resilience is built. The metaphor of change that captures this is the adaptive cycle (HOLLING, 1986); after a system attains maturity it begins ageing and the system becomes increasingly vulnerable to internal and external disturbances. When the system's resistance is less than the level of extrinsic force exerted by a perturbation, the system enters a breakdown and release phase, and a new cycle of maturation and breakdown is initiated. This constant renewal activity provides for adaptation to a changing environment. Ecological resilience is the amount of change a system can undergo while retaining its structure and functions. Elasticity or "engineering resilience" is a measure of how long it takes for the system to attain its pre-disturbance state. However, this trajectory depends on ecological memory; *e.g.* seed banks, saplings and refugia for mobile species, If the disturbance's magnitude is large enough to erase this ecological memory, the system is likely to be tripped to a new configuration or state; low frequency but very intense events (*e.g.*, wind storms, tsunamis, extremes in precipitation and temperature, or prolonged drought) and chronic long-term disturbances (*e.g.*, changes in hydrology produced by dams, embankments, dikes, dredging and spoil deposition) reduce the size of the stability domain and create susceptibility (pre-stressing) for triggering rapid reconfiguration to a different ecosystem. Such transitions may be elicited by low level disturbances (SCHAEFFER-NOVELLI et al., 2015).

Coastal wetlands, *i.e.*, mangrove and salt marsh ecosystems, maintain coastal water quality and reduce the severity of infrequent but highly consequential storms, waves and flood damage. Hydrodynamic transport disperses organisms and organic aggregates widely over the whole system (NELLEMANN et al., 2009), this provides for rapid regeneration and renewal after severe disturbances that cause extensive local damage. It also provides for widespread carbon trapping in diverse places and landforms. These areas are important nursery and feeding grounds for many benthic and pelagic species, many of them with high commercial value (ENGLISH et al., 1997) as well as for long-term carbon sequestration. The conservation of coastal zones must be focused on passive measures that enhance robustness, where robustness is related to the duration or longest time span (endurance) of a structure. This is contingent on effective social engagement at all levels. A commitment to endurance requires a multigenerational societal commitment solidly grounded on education.

Global warming

Changes in temperature, precipitation and extreme events (*e.g.*, hurricanes, storms, etc.), driven by increased atmospheric CO_2 concentrations are important agents that increase the impacts related to rising sea levels in wetlands. The responses of mangrove forests and salt marshes to climate change result from the interaction of these factors with local processes and non-climatic stressors that reduce the ecosystems' resilience (ALONGI, 2008; WEBB et al., 2013; UNEP, 2014).

An analysis of climate data of the last four decades indicates a trend of warming atmospheric temperatures all along the Brazilian coast (BERNARDINO et al., 2015). The present scenarios suggest that the increase in air and water surface temperatures may alter the distribution and composition of species, increase or decrease productivity (depending on intensity), increase respiration rates and modify the reproductive phenology of mangrove forests and salt marsh species (FIELD, 1995; CHEESEMAN et al., 1997; SOARES et al., 2012). Increased rates of rainfall may raise silt deposition rates, plant productivity and diversity and alter species distribution (ELLISON, 2000, 2015; KRAUSS et al., 2003; WHELAN et al., 2005).

Studies in the early 1980s indicate that salt marsh community transpiration is raised by thermal stress (HUTCHINGS; SAENGER, 1987). Recent studies indicate that the physiological responses of mangrove forest and salt marsh plants are sigmoidal (manifesting an increase, a plateau and a decline). However, the threshold leading to the decline remains uncertain (ALONGI, 2015).

Higher temperature increases carbon turnover and metabolism in salt marshes and mangrove forests (HUTCHINGS; SAENGER, 1987; ALONGI, 2015). The rise in temperature results in faster growth, reproduction, photosynthesis, respiration, changes in community structure, diversity, and an expansion toward higher latitudinal limits (ALONGI, 2015).

The ongoing poleward encroachment of mangroves on salt marshes is mostly due to the rise in surface temperature that increases propagule production, dispersal, and establishment (REID; BEAUGRAND, 2012; ALONGI, 2015).

Extreme weather events

Cyclonic storms, and strong convective systems and and other low frequency but highly consequential events are expected to become more frequent due to increased warming of the terrestrial surface. Mesoscale Convective Systems (MCSs) are a complex of thunderstorms that may produce strong squall lines, downbursts and tornados. These events are generated by the warming of the terrestrial surface and have lifespans of several hours (FERREIRA, 2006). They can act over large swathes of terrain and leave significant legacies in terms of localized damage. The scale and intensity of systems like these can result in mass mortalities, erosion, siltation, and decreased plant productivity (JIMENEZ et al., 1985; ALONGI, 2008; YANAGISAWA et al., 2009). Brazil has even experienced unprecedented types of disturbance that had not been previously recorded. On March 2004 a tropical cyclone struck the coast on the border between the states of Santa Catarina and Rio Grande do Sul with winds reaching more than 100 km/hr. and waves more than 5m high near the coast (FERREIRA, 2006). Such phenomena are extremely unusual in the South Atlantic. Previously only two other instances of cyclonic disturbances in the South Atlantic had been recorded, but these never reached the coast, dissipating offshore. Generally, although surface water temperatures may be briefly suitable for cyclonic development, the structure of upper level winds is not conducive to storm development. This unusual event suggests that unprecedented weather phenomena can develop as a result of increased warming and the brief convergence of transient but favorable conditions. Furthermore, it also highlights that the observational record and data coverage has been too limited to “capture” the full spectrum of meteorological phenomena, and that what are considered anomalies might not in fact be so.

Global predictions for the period between 2081-2100 indicate a decrease of between 10 and 40% in rainfall for northern South America, and an increase of up to 10% in eastern South America, both relatively to the 1986-2015 reference period (COLLINS et al., 2013). Both areas are predicted to show an increment of up to 0.5% in salinity (COLLINS et al., 2013).

Mangrove forests in the wet tropics have greater biomass and productivity than do arid zone stands. Trees are taller but less dense (ALONGI, 2015). A rainfall deficit could lead to a loss of mangrove areas due to declines in productivity and the survival of seedlings and changes in interspecific competition (FIELD, 1995; ALONGI, 2008).

The Southeastern coast of Brazil (including the states of Rio de Janeiro, São Paulo, and Paraná) has shown an increase in rainfall recently (BERNARDINO et al., 2015). In general, precipitation is expected to remain the same but not to be uniformly distributed, occurring in short isolated events usually associated with high winds and flooding events associated with intense downpours which are expected to be disruptive to wetlands.

It is expected that structural and functional changes will occur intermittently, driven and accelerated by extreme events such as storms causing alterations in both flooded and in mature forests at the interface with newly submerged lands. In the case of storms, the relatively shallow root system is especially vulnerable to the action of waves and current scour. Thus, the most likely scenario would be sporadic marine transgressions, followed by periods of minor change (SCHAEFFER-NOVELLI et al., 2002) and perhaps change in coastal configuration over periods of decades and progressive inland migration with increased salinization. Severe storms would result in greater impact, with significant destruction of the vegetation cover of salt marshes, where the root system is more vulnerable, as at the outer edge, removing entire clusters of plants, as occurs annually and cyclically as a consequence of winter disturbances.

Sea level rise

Sea level has varied dramatically over the course of the Earth’s history with repeated variations exceeding 100m from the present sea level. Coastlines colonized by mangroves and salt marshes have been exposed to extensive and virtually continuous disruptions as a result of sea level fluctuations over geological time (WOODROFFE, 1992). Approximately 6,000 yrs ago, marine transgressions slowed down, and the sea level became relatively stable (NATIONAL RESEARCH COUNCIL, 1990).

The melting of the polar caps has been the most significant factor involved in increasing the volume of the oceans; and a coastline exposing such ecosystems to wave energy has reshaped them into a new sea level configuration during this time, though local-level has varied greatly due to site and regional factors (BLOOM; YONEKURA, 1990; WOODROFFE, 1992). Some local effects such as those induced by the estuarine type (*e.g.*, size and configuration) have been associated with oscillations in sea level (see BEERBOWER, 1964).

In Brazil, studies conducted in the *apicum* facies have revealed the presence of fossil mangroves, indicating that the sea reached higher levels than at present (SORIANO-SIERRA et al., 1998; SAINTILAN; WILLIAMS, 1999; SOARES et al., 2000; SCHAEFFER-NOVELLI et al., 2002; BEHLING et al., 2004; COHEN et al., 2005; STEVENS et al., 2006; SOARES, 2009; HADLICH; UCHA, 2009; FRIESS et al., 2012).

Several temporal scales are involved when examining sea level change; large scale tectonic plate changes are of the order of 10^6 - 10^9 yrs; an intermediate span involves changes related to eustatic variations due to glaciation, which are of the order of 10^3 - 10^6 yrs. (Some tectonic forces also act on this scale). Short-term changes of the order of hours to 10^3 years also take place, and involve astronomical tidal processes and changes related to continuous accommodation to the Holocene transgression. The last few millennia have been a time of high and relatively stable stand after 100 millennia of rapidly changing levels. This brief span of relative stability has shaped the present coastal environments but coastal morphology varies widely even over short distances not only because coastal processes vary in temporal scale, but landforms also evolve at different rates. This condition of stability is expected to change with the advent of greenhouse gas-induced climate change.

Medium-term climatic change will be reflected in sea level change through three processes; 1) the melting of ice in continental ice caps and glaciers; 2) variations in the amount of water stored in lakes and rivers, and 3) steric changes (changes due to thermal expansion). Steric height change has been shown in regional studies to account for seasonal and interannual changes of the order of 100mm (NATIONAL RESEARCH COUNCIL, 1990).

In any case the temporal hierarchy of the processes regulating sea level is important in understanding and assessing how mangrove and salt marsh ecosystems will respond in space and time to sea level change. At least five spatio-temporal frames of reference are involved in coastal processes that represent fairly discrete but interacting forcing domains: 1) Coastal Geomorphology, reflecting tectonics and the general character of sedimentation; 2) Regional, reflecting the dominance of particular processes such as that of waves, rivers or tides; 3) Landscape/Physiographic, reflecting specific terrigenous settings and mangrove/ salt marsh habitats; 4) local/stand, reflecting processes at individual landform level, and 5) Site or sub-local, involving greater detail of microtopographical structure within a given landform. This physiographical approach, derived from THOM (1984), provides a flexible way to interpret habitat dynamics on multiple scales. Changes at the higher levels occur at a slower (multi-decadal or more) pace, and act as constraints that buffer change at the lower levels. Climate-induced change triggers instability at the "instantaneous", event scale as well as the "engineering scale" of coastal processes triggering immediate and lasting impacts on human and societal activity (COWEL; THOM, 1994).

High level physiographic and biotic organization provides sustained resistance and resilience. At the lower levels local resilience is expressed as elasticity; manifested in the capacity for regenerating local structure quickly. However, robustness, manifested as persistence, resides in higher level structures and landscape processes that involve the integrity of the whole physiographic unit. In the recent ecological literature the attributes described as "Ascendancy" and "Overhead" (ULANOWICZ, 1990, 1997) seems appropriate to understanding the dynamics of coastal systems. Ascendancy is related to the power or "clout" of a system and its performance. This attribute can be related to size. "Overhead" is the capacity of the system to adapt to the unexpected. It resides in systemic diversity and the redundancy of pathways that can be reconfigured to deal with the unexpected.

Resilience implies not only capacity to respond to expected behavior, but being nimble enough to reorganize and respond to the unprecedented. "Overhead" provides for systemic "breadth" or reliability and ultimate persistence; that is, sustainability. We highlight this because sustainability is often taken to be related to the capacity to bounce back leading to erroneous notions such as "maximum sustained yield" that ignores evolvability, the capacity of the system to react at the genetic level to changing requirements for survival. The mere capacity of a system to return to an earlier state is not sustainability. Ecological resilience is a more useful tool for assessing a system's response to large disturbances and its capacity to persist. Ecological resilience draws attention to multiple scale and cross-scale dynamics. For a more detailed description of these attributes and possible applications in resource management see ULANOWICZ (1997, 2009). Here we suggest these attributes can play a key role in understanding impacts of climate change and in providing insights on how to deal with inevitable environmental change.

The massive human occupation of the tropical and subtropical coastline has been playing a major role in the configuration of coastal ecosystems. Although their resilience regarding climate change and changes in sea level has been proven, anthropogenic pressures have pushed them almost to their limit; due to the accelerated speed of change dwindling in size, and the internal degradation of ecosystems. This diminishes their response capacity delaying replacement and restoration of damaged structure and functions to pre-disturbance levels, weakening the capacity to deal with recurrent events.

Effects on mangrove forests and salt marshes may vary from loss in root biomass and in substrate stability to the destruction of above ground structure by undermining and edge scour, causing vegetation coverage to diminish. This process is very similar to that described by SEMENIUK (1980) along the northwest coast of Australia. According to this author, 'sheet' erosion occurs more readily during neap tides, due to the extensive exposure of the tidal flats to desiccation through evaporation, favoring the growth of salt crystals and the disruption of mud aggregates. Later spring tides fills the cavities (*e.g*., crab burrows) and salt crystals dissolve; loosening the mud, which when it collapses, becomes a dense suspension. The suspended particles are then transported by ebb currents to the sea (VALE, 2010). These effects will be less intense in mesotidal and microtidal environments such as those in Brazil where scouring is reduced and where dense root mats can provide higher levels of substrate stability. However, similar conditions may occur on the Northern Brazil macrotidal coast, where extreme tidal amplitude and seasonal episodes of extreme rainfall-driven flooding trigger severe scouring.

Coastal areas might suffer alteration in sediment budgets, transforming sinks into sources and *vice versa*. The local and landscape level transport of sediment may be intensified by increases in scouring and erosional rates (MARINS et al., 2003; CUNHA-LIGNON et al., 2011).

Relative sea level curves have been proposed for several sectors of the Brazilian coast. There is, however, no sea level curve with general applicability in view of the fact that each coastal segment has a particular «energy signature» (*sensu* ODUM, 1969) and is subject to local controls. Relative changes in sea level in a given area are dependent on the interplay between eustasy, local tectonics, and rates of sedimentation as well as endogenous change due to changing geometry.

Due to these local and regional differences in Brazil the landscapes of the middle and upper Holocene include mangrove environments that are both transgressive and regressive. Data suggests a Holocene sea-level maximum between 3.5 and 4.5m above the present level. The paleoclimatic records of the Juréia paleolagoon in São Paulo (Brazil) reveal cyclical climate changes correlated with successive transgression-regression episodes in the Holocene (SALLUN et al., 2012). Such anomalies are observed in the Quaternary sediments of paleolagoons (between 7,500 and 9,400 yrs BP) and are correlated with natural events generating high rates of sedimentation (10 cm/yr). This suggests that short-term (interdecadal) meteorological events such as those that occur in the North Atlantic, can significantly affect the environment in South America, intensifying summer monsoons (SALLUN et al., 2012).

Mangrove ecosystems have proven to be highly competent in dealing with moderate rates of variation in mean sea level, frequency of flooding, and sediment supply (ALONGI, 2008) if their resilience has not been compromised by other factors such as drought, diversion of hydrologic inputs, and change in tidal regimes (amplitude and frequency). For example, at the delta of the Ganges River a difference in relative sea level of 10-15 mm/yr, is small compared to the amplitude of the macrotidal regime allowing adaptations in mangrove coverage to occur (WOODROFFE, 1990). However, in a microtidal regime such as that in Bermuda (Caribbean Sea), an increase of only 2.8 mm/yr promoted a reduction in sediment deposition rates below the level required for mangrove persistence, resulting in the loss of this ecosystem (ELLISON, 1993, 2015). In contrast, salt marsh ecosystems present high tolerance to flooding, surviving under more than a meter of permanent flooding, as observed in the Conceição Lagoon (Santa Catarina State, Brazil) (SORIANO-SIERRA, 1989).

The ability to recover after a disturbance is an attribute of the environment as a whole and not of a unique plant *per se* (GRUBB; HOPKINS, 1986; SCHAEFFER-NOVELLI et al., 2005). In a scenario of rapidly rising mean sea level, it is reasonable to expect the disappearance of mangrove forests and salt marshes in exposed littoral zones due to the loss or overtopping of buffering structures (*e.g*., barriers and similar coastal features that protect from waves and storms) as well as in marginal environments (unsuitable substrates or highly disturbed areas).

The greater development of mangrove forests could be expected in environments characterized by drowned river valleys under maximum sedimentation and large tide amplitudes. These areas would serve as reservoirs and reliable sources of mangrove propagules during periods of very rapid changes in the coastline (SCHAEFFER-NOVELLI et al., 2002; ALONGI, 2008). The recovery rate (elasticity) of typical mangrove and salt marsh plants depends not only on the pioneering properties of these plant species (as r-strategists), but on the landscape-level connectivity among sites and dispersion processes, as indicated earlier. This allogenic resilience occurs as a function of the proximity to propagule sources and the existence of appropriate mechanisms for dispersion and transport (LEWIS, 2005).

Plants located in lower tidal elevations are more likely to be impacted. Most salt marshes show particularities in their responses to flooding. With an increasing influence of seawater, essential nutrients may be limited due to ionic effects, as the plants' ability for their uptake is likely to change (DAWES, 1998). Long periods of tidal immersion may result in many negative impacts to the salt marsh plant communities, including: (1) loss of leaves, due to the mechanical effects of tidal currents; (2) death of individuals, due to temperature shock; (3) physiological distress, due to changes in photoperiod, and (4) siltation of leaves, and mortality, due to the blockage of stomata (DAWES, 1998).

On higher ground, above normal tidal incursions, the *apicum facies* of arid mangrove areas acts as a reservoir of nutrients and supports the developmental stages of some mangrove-associated invertebrates (LACERDA et al., 2001). Prokaryotic cyanophytes are important nitrogen fixers, and nitrogen can be leached or transported by terrestrial drainage, run off, and the ebb tide, thus enriching the adjacent mangrove forest (PALING; MCCOMB, 1994; PALING et al., 2003).

Rising carbon and methane gases in the atmosphere

Increased concentration of atmospheric CO_2 is expected to promote higher photosynthetic rates and growth in mangrove forests (UNEP, 1994; BALL et al., 1997), but this can be limited by the physiological thresholds imposed by water deficits and higher salinities, caused by increased evapotranspiration that diminishes net production.

ALONGI (2015) reported that the red mangrove (*Rhizophora mangle*) maturation is stimulated by increased CO_2 concentrations during experiments. Growth was enhanced by both high CO_2 and low salinity (ALONGI, 2015). *Rhizophora mangle* is an abundant species in most Brazilian mangrove forests. Another very common species in Brazil, exclusive to the Atlantic Ocean, is the white mangrove (*Laguncularia racemosa*). Studies show that this species' net primary production, stomatal conductance, and transpiration are compromised by increasing CO_2. There was, further, an increase in transpiration efficiency (SNEDAKER; ARAÚJO, 1998). Such metabolic responses might change the composition of mangrove stands, as well as their phenology, completely.

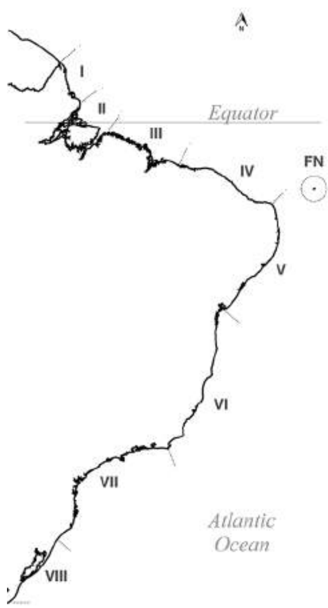
The decline in the ocean's pH has already been observed, due mainly to the higher concentration of greenhouse gases, especially CO and CO_2, in the atmosphere. This is expected to have little or no impact on mangrove forests, due to the daily variation in tidal inundation and soil pH (ALONGI, 2002). Finally, the disruption of salt marshes and mangrove forests could promote significant impacts on sequestration that in their turn could lead to the release of large amounts of stored carbon into the atmosphere (AUSTRALIAN GOVERNMENT, 2012). Carbon releases include methane gas which has a global warming potential 21 times higher than CO_2. The extra methane in the atmosphere contributes greatly to climate change (ARCHER, 2010).

Mangrove forests and salt marshes export particulate matter (*e.g.*, detritus, leaves, twigs, seedlings) that further decomposes in adjacent water bodies (*e.g.*, rivers, estuaries, coastal waters), transforming detritus into organic particulate bacterial/detrital aggregates and dissolved organic matter (HUTCHINGS; SAENGER, 1987; JAFFÉ et al., 2004; DUNN et al., 2008). Inland along the mangrove *continuum*, in shallow depressions, basin-type mangals occur (LUGO; SNEDAKER, 1974). Much of the litter in these systems is decomposed and exported as dissolved organic matter (DOM) or finer particulate matter, which is of great ecological relevance to adjacent areas (SCHAEFFER-NOVELLI et al., 2002). Besides their role in exporting organic matter, mangrove and salt marsh ecosystems are carbon sinks, storing it in aerial (leaves and wood) and underground structures (SEMENIUK, 1980; NELLEMANN et al., 2009; HUXMAN et al., 2010; BOUILLON, 2011; DONATO et al., 2011).

The role of both mangrove areas and salt marshes is critical as they are biological carbon processors that are coupled to oceanic transport mechanisms via tidal action and currents, which results in carbon dispersal and deposition in shelf or deep water reservoirs (BAUER et al., 2013) where carbon can be immobilized for decades, centuries or even millennia (SCHAEFFER-NOVELLI et al., 1990).

Final considerations

Climate impacts are not manifested as singular pulses and effects on the landscape. Rather, impacts cascade over a complex network of relationships eliciting a spectrum of responses spread over broad spatial and temporal dimensions, and levels of organization. Exposure to disturbances induces dynamism on the annual and decadal scales that is reflected in changes in the populations, biomass, and spatial distribution of the biota. Together, geomorphology, topography, regional and local climate, and disturbances produce heterogeneity creating a tapestry that reflects a complex history of continuous disruption and regeneration. Because of this inherent dynamism species have come



I. In this segment mangrove forest display high levels of aggregate self-organization that reduces chaotic behavior and confers a greater propensity to preserve order amid change. The systems here act as attractors that buffer irregularity and slow down change. Because of its size and vigor this forests entrain the capacity to adapt more successfully insuring relative stability and endurance and ability to cope with short term weather-driven disturbances. Salt marshes are a minor important features of this areas. Coastal marshes are geologically ephemeral and grow and decline in response to geomorphic and climatic events. Complex irregular patterns and local change can be attributed to site-level variations in environmental controls and external stochastic forcing, resulting in highly variable local dynamics within a larger more stable geomorphic unit.

II. This segment is highly dynamic in terms of hydrology and sedimentary activity where fresh water assemblages currently tend to dominate. This dynamism is likely to persist in spite of climate changes although it could be expected that the processes would become increasingly variable. We would expect that this increase variability could become manifested in the predominance of successional *facies* between mangroves and "aninga" (*Montrichardia arborescens*) stands. Ephemeral mud banks are often rapidly colonized by salt tolerant grasses and herbaceous species.

III. This segment is characterized by high level of biomass aggregation and system activity that can ensure persistence in spite of increased environmental variability. Sea level rise is expected to favor both inland penetration of mangroves as well as outward expansion. Salt marshes are important features of this areas, but are likely to be more vulnerable to direct or indirect climate change. Currently the major threat to mangroves is unsustainable harvesting of mangrove wood even inside Conservation Units.

IV. This segment is arid, and characterized by short estuaries, and a watershed vulnerable to extreme droughts. Mangrove systems here are spatial limited and more likely to be severely disrupted and temporarily eliminated by stochastic events. Salt marshes are a minor important features of this areas, and may respond in a similar way as mangroves to climate changes. The conjunction of severe environmental constraints (drought, high temperatures) and human-induced stressors (shrimp farming, salt pans and tourist developments) can result in indeterminate outcomes. The still abundant mangrove *apicum facies* is being threaten by these unsustainable developments.

V. In this segment the mangroves are expected to diminish further due to higher salinities, thermal stress and increasing climatic variability. The coastal hydrology is driven by deep drought events in the interior. Salt marshes are a minor important features of this areas, and may respond in a similar way as mangroves to climate changes. The still abundant mangrove *apicum facies* is being threaten by unsustainable developments such as human-induced stressors (shrimp farming and tourist developments) reducing resiliency and favoring indeterminate outcomes.

VI. This segment is characterized by extensive large embayments that can act as natural substrates for mangrove and salt marsh occupation. The more significant threats are non-climatic (shrimp farming, tourist developments and the oil production), these reduce resilience to cope with environmental change. Salt marshes are a minor important features of this areas, but are likely to be more vulnerable to direct or indirect climate change.

VII. This segment is also reach in physiographic complexity, which favors mangrove development but is also an area of extreme human occupation in terms of urban and industrial development as well as coastal pollution. In the southern end this segment salt marshes acquire greater dominance increasing the establishment of more complex relationships between both systems, behaving as a higher hierarchical unit; a macro (eco)system.

VIII. Presently this segment is beyond the latitudinal limit of mangrove distribution, however there is evidence of paleomangrove environments. This coastal segment is dominated by extensive elongate brackish coastal lagoons that are partially occupied by extensive marshes.

(FN) Fernando de Noronha Archipelago. Oceanic climate favours an arid climatic regime. There is a single mangrove stand in the main island fed by an intermittent stream that was dammed to build a water reservoir. This stand consists of approximately 40 mature individuals of *Laguncularia racemosa* in a basin between sand dunes and the shoreline. Sea water enters intermittently through a saddle in the outer marginal dune as storm swash, and perhaps percolates into the basin between storm events.

Figure 1. The assessment of the impact of climate change on mangrove forests and salt marshes along the Brazilian coast.

to possess adaptations that allowed them to resist and to recover when challenged by natural disturbances if this resilience is not compromised.

Traditional management has been focused on the increase and optimization of economic growth and production, undervaluing or ignoring critical ecological services including self-organization. Climate change demands that the aims of management be the same of those instead as conservation. The importance of pursuing integrated "win-win" and "no-regrets" solutions is more critical than ever to address climate change issues (IPCC, 2012). Sustainable development is inherently a "win-win" "no-regrets" solution when coastal systems with large capacity for carbon sequestration are integrated into climate adaptation strategies.

In a nut shell, the above solutions can be developed through actions that: 1) delay or buffer climate impacts; 2) mitigate impacts through restoration; 3) increase overall resilience and facilitate natural recovery, and 4) reduce non-climate threats and eliminate conversion and reclamation of wetlands.

Based on the classification of SCHAEFFER-NOVELLI et al. (1990), we provide a summary of expected effects of the impacts of climate changes on Brazilian mangrove forests and salt marshes (Figure 1).

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Seagrass and Submerged Aquatic Vegetation (VAS) Habitats off the Coast of Brazil: state of knowledge, conservation and main threats

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ABSTRACT

Seagrass meadows are among the most threatened ecosystems on earth, raising concerns about the equilibrium of coastal ecosystems and the sustainability of local fisheries. The present review evaluated the current status of the research on seagrasses and submerged aquatic vegetation (SAV) habitats off the coast of Brazil in terms of plant responses to environmental conditions, changes in distribution and abundance, and the possible role of climate change and variability. Despite an increase in the number of studies, the communication of the results is still relatively limited and is mainly addressed to a national or regional public; thus, South American seagrasses are rarely included or cited in global reviews and models. The scarcity of large-scale and long-term studies allowing the detection of changes in the structure, abundance and composition of seagrass habitats and associated species still hinders the investigation of such communities with respect to the potential effects of climate change. Seagrass meadows and SAV occur all along the Brazilian coast, with species distribution and abundance being strongly influenced by regional oceanography, coastal water masses, river runoff and coastal geomorphology. Based on these geomorphological, hydrological and ecological features, we characterised the distribution of seagrass habitats and abundances within the major coastal compartments. The current conservation

RESUMO

Pradarias de gramas marinhas e vegetação aquática submersa (VAS) estão entre os ecossistemas mais ameaçados do planeta, gerando preocupação sobre o equilíbrio dos ecossistemas costeiros e a sustentabilidade das pescarias. A presente revisão avaliou o estado do conhecimento sobre as pradarias marinhas e VAS do Brasil, considerando as respostas das plantas às condições ambientais, e o possível papel da geomorfologia costeira e variabilidade climática sobre a distribuição e abundância das populações. Apesar do crescente aumento no número de publicações, a comunicação dos resultados ainda é relativamente limitada e destina-se principalmente ao público nacional ou regional. Como resultado, as pradarias de gramas marinhas da América do Sul raramente são incluídas ou citadas em revisões e modelos globais. A escassez de estudos em larga escala e de longo prazo, permitindo a detecção de mudanças na estrutura, abundância e composição dos habitats e espécies associadas, limita a investigação das comunidades no que diz respeito aos efeitos potenciais das mudanças climáticas. Pradarias marinhas e VAS ocorrem ao longo de toda a costa brasileira, mas a distribuição e abundância das espécies são influenciadas pela oceanografia regional, massas de água costeiras, descarga de rios e geomorfologia costeira. Com base nas características oceanográficas, geomorfológicas, hidrológicas e ecológicas, o estudo discutiu a distribuição e abundância dos habitats vegetados pelas distintas regiões costeiras. O estado de conservação das pradarias marinhas

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status of Brazilian seagrasses and SAV is critical. The unsustainable exploitation and occupation of coastal areas and the multifold anthropogenic footprints left during the last 100 years led to the loss and degradation of shoreline habitats potentially suitable for seagrass occupation. Knowledge of the prevailing patterns and processes governing seagrass structure and functioning along the Brazilian coast is necessary for the global discussion on climate change. Our review is a first and much-needed step toward a more integrated and inclusive approach to understanding the diversity of coastal plant formations along the Southwestern Atlantic coast as well as a regional alert the projected or predicted effects of global changes on the goods and services provided by regional seagrasses and SAV.

Descriptors: Seagrasses, SAV, Distribution, Antropogenic impacts, Global climate change, Climate variability.

e VAS no Brasil é extremamente crítico. A exploração insustentável e ocupação da zona costeira durante os últimos 100 anos conduziram à rápida degradação e perda de muitos dos habitats bentônicos marinhos e costeiros, outrora favoráveis para a ocupação da vegetação aquática. O conhecimento sobre os padrões e processos que regem a estrutura e o funcionamento destas populações e comunidades é fundamental para prever e compreender os efeitos das mudanças climáticas. A presente avaliação é um primeiro passo, necessário para uma abordagem mais integrada e inclusiva sobre a diversidade de formações vegetais costeiras ao longo do Atlântico Sudoeste, bem como um alerta regional a respeito dos efeitos previstos das mudanças climáticas das mudanças globais sobre os produtos e serviços ecossistêmicos prestados pelas pradarias marinhas.

Descritores: Pradarias marinhas, VAS, Distribuição, Impactos antrópicos, Mudanças climáticas globais, Variabilidade climática.

INTRODUCTION

Seagrass meadows and coastal submerged aquatic vegetation (SAV) constitute complex habitats that influence the physical, chemical and biological characteristics of coastal environments, acting as ecological engineers and providing a number of services to marine systems and human populations (ORTH et al., 2006). These habitats are dominated by rooted plants that primarily colonize soft marine sediment on shallow coasts under low-to-moderate energy (KEMP et al., 2004; DENNISON et al., 2008). Seagrasses are a particular and homogeneous group (phylogenetic related) of rooted and flowering plants confined to the estuarine and marine environment that are able to live and complete their life cycle under submerged and haline conditions (DEN HARTOG; KUO, 2006). SAV are plants that live below or at the water surface, and it is a general term for prairies within estuaries and freshwater environments; it includes seagrasses, freshwater grasses and macroalgae species (KEMP et al., 2004; DENNISON et al.; 2008). Recognizing that both seagrass meadows and SAV have similar ecological functions, are affected by similar physical drivers and are highly threatened by anthropogenic impacts, this review will use the two terms interchangeably.The capacity of SAV and seagrasses to physically and chemically engineer their environment and to supply coastal protection - among the many services and benefits human populations may obtain from the ecosystem functions (KOCH, 2001; MILLENNIUM ECOSYSTEM ASSESSMENT, 2005) - has been largely evidenced in European, Australian and U.S. coastal regions. The plant canopy buffers the impact of waves, protecting the coast and shallow bottoms from erosion. By reducing current velocity, the plant canopies promote the deposition of suspended matter, increasing water transparency within and adjacent to the meadows. The rhizome net traps and stabilizes the sediments, contributing to sediment accretion, the accumulation of organic matter and carbon sequestration. Seagrasses and SAV improve water quality by oxygenation and by removing excess nutrients and other pollutants from river and runoff inputs (KOCH, 2001; SHORT et al., 2007; BARBIER et al., 2001). Due to their structural complexity and high primary production, they provide food and nursery habitats for many invertebrates and fish; many economically important fish and shellfish species depend on seagrass beds during critical stages of their life cycle (ORTH et al., 2006; WAYCOTT et al., 2009). Seagrass and SAV habitats also provide forage for many aquatic birds and endangered species, such as seahorses, sea dragons, sharks, sea turtles, dugongs and manatees (BJÖRK et al., 2008; HEMMINGA; DUARTE, 2000). They also have important aesthetic and cultural values, providing leisure and sustaining tourism activities such as snorkeling, diving, fishing and fauna watching (BJÖRK et al., 2008). In the past they have been used as mattress filling, roof covering, house insulation, garden fertilizers (BJÖRK et al., 2008) and in traditional medicine (DE LA TORRE-CASTRO; RÖNNBÄCK, 2004), as well as for spiritual uses (LAUER; ASWANI, 2010).

Together with mangroves and salt marshes, seagrass meadows are among the largest carbon sinks in the ocean - more than half of sequestered carbon is located beneath these systems despite their covering only 0.5% of the seabed (MCLEOD et al., 2011; FOURQUREAN et al., 2012; DUARTE et al., 2013). Their associated sediments contain 2 to 15 times more carbon per hectare than terrestrial soils (FOURQUREAN et al. 2012). Furthermore, the rate at which these coastal systems sequester carbon is 10 to 50 times greater than the rate of carbon sequestration by terrestrial forest systems, and this carbon can be sequestered by the climatic system on timescales of centuries or even millennia. Therefore, seagrass meadows play a fundamental role in the global carbon cycle with the potential to mitigate climate change (DUARTE et al., 2013). Within this scenario, protecting and restoring seagrass meadows may be used in the near future as an offset in carbon budgets (LOVELOCK; MACALLISTER, 2013). The economic value of the world's seagrass meadows has been estimated (COSTANZA et al., 1997; LARKUM, 2006; UNSWORTH et al., 2010; BLANDON et al., 2014; VASSALO et al., 2014; COSTANZA et al., 2014; TUYA et al., 2014), and it may vary from US$ 968 to US$ 2 million ha^{-1} y^{-1} depending on the region, included services and methodology applied. Globally, seagrasses can provide ecological services worth more than US$ 20 billion a year (ORTH et al., 2006), a value 33 and 23 times higher, respectively, than the average oceanic and terrestrial values, being 3 times greater than that of coral reefs and 10 times greater than that of tropical forests (BJÖRK et al., 2008). These values should increase considerably when the value of carbon sequestration is added in the near future.

The global distribution and abundance of seagrasses and SAV has changed gradually over time (the last 70-80 million years) in response to sea-level changes, physical modification of coastlines, changes in atmospheric carbon dioxide concentration (ppm CO_2), sea surface temperature (CROWLEY, 1990; BERNER; KOTHAVALA, 2001) and herbivore-seagrass interactions (DOMNING, 2001). While spreading and undergoing continued change and adaptation to regional environmental drivers, seagrass habitats have been modified by current changes to the coastal zone resulting from increased human pressures and recent changes in the global climate. Over the last 40 years, seagrass losses have increased almost tenfold in both tropical and temperate regions, suggesting that seagrasses are facing a global crisis (ORTH et al., 2006). It is believed that at least ~30% of their known extent in terms of area has disappeared since the end of the 19th century (WAYCOTT et al., 2009), a number that is certainly underestimated because it was mainly based on European, North American and Australian studies. The loss rates have accelerated since 1990 (from 2% to more than 7% yr^{-1}), placing seagrass meadows among the most-threatened ecosystems on earth. Because seagrasses, known as "coastal canaries" (ORTH et al., 2007), are good indicators of water quality and biological health, their reduction and loss are raising concerns about systems' equilibrium and the sustainability of local fisheries (LARKUM et al., 1989). This decrease disrupts important linkages between seagrass meadows and other habitats (HECK et al., 2008), and their ongoing decline is likely to produce much more far-reaching and long-lasting impacts than the loss of the meadows themselves.

Many seagrass species are highly vulnerable to global climate change, mainly due to the effects of the increase in atmospheric and sea surface temperature, sea level rise (causing salinity intrusion, changes in tides, currents and depth of light penetration), increases in the frequency and intensity of extreme events and ocean acidification (see SHORT; NECKLES, 1999; DUARTE, 2002 for reviews). In the mid- or long-term, there will be impacts on distribution abundance, population structure and communities, some of which have already been registered (SHORT; WYLLIE-ECHEVERRIA, 1996; SHORT et al., 2006; BJÖRK et al., 2008; CONNOLLY, 2009; WAYCOTT et al., 2009). Changes in seagrass ecological functions and connectivity, caused by both the direct and indirect effects of climate change, will echo throughout adjacent marine ecosystems in the mid- and long-term (SHORT; WYLLIE-ECHEVERRIA, 1996; ORTH et al., 2006; MARTINS et al., 2012); sooner or later, this will affect ecological services, such as coastal protection and fishing resources. Such threats may also compromise the way of life of many traditional communities associated either directly or indirectly with seagrasses (CULLEN-UNSWORTH et al., 2014).

While hundreds of studies about the changes in seagrass abundance can be retrieved from a rapid search of peer-reviewed literature, most of them are limited to North America, Europe and Australia (see WAYCOTT et al., 2009 for a review). In contrast, there is a paucity of studies or records about seagrass losses or changes in South America (SHORT et al., 2006; COPERTINO; SEELIGER, 2010; MARQUES et al., 2015) despite its highly populated coastal region. Approximately 25% of the Brazilian population lives by the coast (more than 512 cities, including 13 metropolitan regions). The Brazilian coast is exposed to environmental problems similar to those experienced by both developed and developing countries (GARRETA; ALVES, 2003). From 1500 to the present, the major impacts have been deforestation, intensive boating activity, destructive anchoring, coastal construction, land reclamation, agricultural runoff, the direct destruction of salt marshes and mangrove forests, marina and port developments, aquaculture expansion, and coastal road constructions, among many others (DIAS et al., 2012). In addition, inadequate knowledge and ambiguous perceptions about the importance of seagrasses and SAV have led to a current lack of specific environmental policies.

The total extent of SAV and seagrass meadows along the Brazilian coast is unknown. The extent of these habitats has been roughly estimated at 20,000 hectares by CREED (2003), who summed up the few most-studied sites for which the areas were then known (Patos Lagoon Estuary in Rio Grande do Sul; Araruama Lagoon in Rio de Janeiro; Itamaracá in Pernambuco; Abrolhos National Park in Bahia). However, this is surely an underestimate because the 9000 km-long linear Brazilian coastline has only been partially mapped to date. In addition to their irregular spatial distribution, seagrasses are highly dynamic and variable on distinct temporal scales. The climatic, hydrological and oceanographic variability along the Brazilian coastline can drive the significant changes in meadow extension and abundances observed over the years and decades (e.g., SHORT et al., 2006; COPERTINO; SEELIGER, 2010; SORDO et al., 2011; BARROS et al., 2013; MARQUES et al., 2015).

The present review aims, therefore, to evaluate the current status of seagrasses and coastal SAV research in Brazil in terms of plant responses to environmental conditions, the indications of change in the distribution and abundance of meadows and the possible role of climate variability (e.g. ENSO, extreme events) and climate change. This study is thus the first analysis of the potential effects of climate change on Brazilian SAV coastal communities. A number of recommendations and guidelines for future research are also presented in the light of their relevance to decision-makers and society as a whole.

MATERIAL AND METHODS

The authors reviewed all research areas and topics (morphology, taxonomy, biochemistry, physiology, ecology, biogeochemistry etc.) available in the literature on Brazilian seagrasses, including associated fauna and flora, through Web of Knowledge, Scopus and Google Scholar. In addition to peer-reviewed articles, we also searched for information in unpublished or published technical reports, conference abstracts, monographs, dissertations, and thesis. We also undertook searches using national and regional databases such as Plataforma Lattes (maintained by the Conselho Nacional de Desenvolvimento Científico e Tecnológico - http://lattes.cnpq.br/), Portal de Periodicos CAPES (maintained by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - http://www.periodicos.capes.gov.br/) and the Scientific Electronic Library Online - http://www.scielo.org/). Brazilian researchers, working on benthic ecology, phycology, aquatic plants as well as coastal geomorphology, were also contacted to contribute information on seagrass occurrence and abundance. A database on Brazilian seagrasses was built with information on georeferenced occurrences, distribution, abundance, reproduction and other ecological parameters; abiotic (water and sediment) parameters; and associated flora and fauna. We performed metrics and graphical analyses by classifying and comparing the studies according to their spatial and temporal scopes, research topics, species analyzed, and date and source of publication. We discussed the distribuition of seagrass habitats as a function of coastal geomorphology and oceanography, within the context of the distintict Brazilian coastal compartments and landscapes (DILLENBURG et al., 2009; DOMINGUEZ, 2009; MUEHE, 2010).

The international literature on the impacts of climate change on seagrasses and submerged aquatic vegetation was reviewed, including the impacts of climate change on the Brazilian climate and coastal zone. We prioritized studies focused on occurring species and their distribution and on how climatic and water parameters affect species physiology and reproductive biology, population parameters and community ecology. The relevant information was integrated to discuss the vulnerabilities of Brazilian seagrass meadows to climate variability, climate change (mainly global warming) and anthropogenic impacts.

RESULTS AND DISCUSSION

Seagrass studies in Brazil: a metric approach

Compared with most coastal benthic ecosystems (mangroves, coral reefs, rocky shores and sandy beaches), Brazilian seagrass beds are poorly studied (BARROS et al., 2013). Despite more than 200 registered database items mentioning seagrasses in Brazil, the authors found no more than 120 publications including articles, thesis and book chapters from 1957 to 2015. Most studies were concentrated in the states of Pernambuco (PE), Rio de Janeiro (RJ) and Rio Grande do Sul (RS) (Figure 1). We analyzed the advance and progress made in knowledge during the last several decades. Before the 1970s, studies were limited to species occurrence and qualitative descriptions of the plants and environment (e.g., CAFRUNI et al., 1978; DEN HARTOG, 1970). During the 1980s, botanical and auto-ecological studies were more common (e.g., LACERDA; RESENDE, 1986; KOCH; SEELIGER, 1988; COSTA; SEELIGER, 1989), whereas papers on population ecology and ecophysiology increased during the 1990s. From then on, there was an increase in community studies, with very few ecosystem approaches (e.g., SILVA; ASMUS, 2001). The steady increase in the number of seagrass studies during the last few decades, particularly after the 1990s, is a trend observed around the world (Figure 2). Today, we are in a phase where reviews, data compilation, integrated studies and projects are finally being prioritized. Approximately 82% of the studies were classified as only descriptive, 8% were categorized as experimental and/or modeling and 10% were reviews (Figure 3a). Most of the work focused on marine angiosperms and their associated fauna, with few studies investigating the occurrence of epiphytes and other associated primary producers (Figure 3b). In addition, less than half of these works simultaneously assessed the effects of environmental variables on the flora and fauna. Among the species of phanerogams that occur along the Brazilian coast, *Halodule wrightii* and *Ruppia maritima* are the most studied (Figure 3c), reflecting their wider distribution and higher abundance on the Brazilian coast.

Analyses of temporal variability in abundance and distribution of seagrass beds and associated fauna have been more common (Figure 3d). Seasonal analyses (as

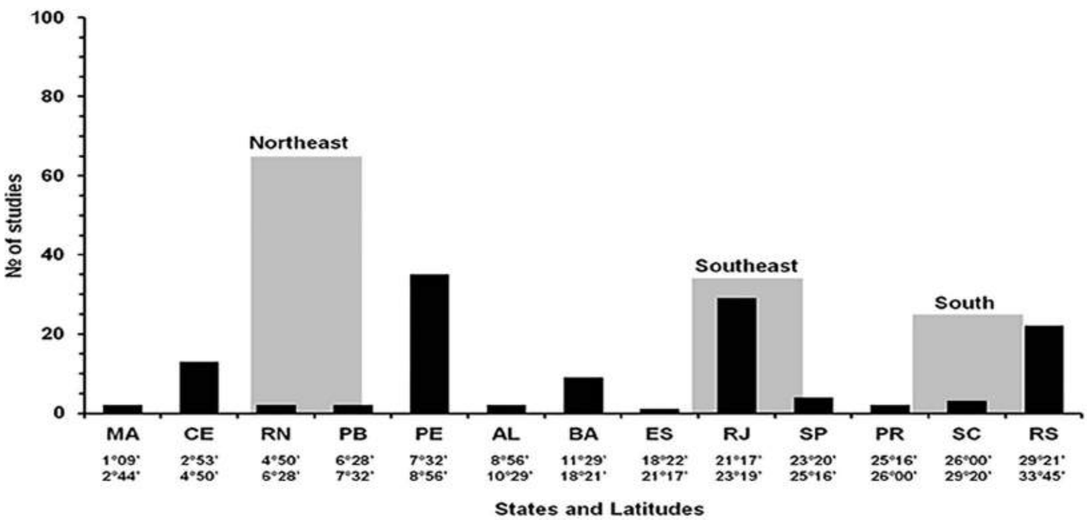

Figure 1. Number of publications (articles, thesis, dissertations, book chapters) containing information about seagrass habitats across the coastal latitudinal range of Brazil, counted per geographic region (grey columns) and federal state (black columns).

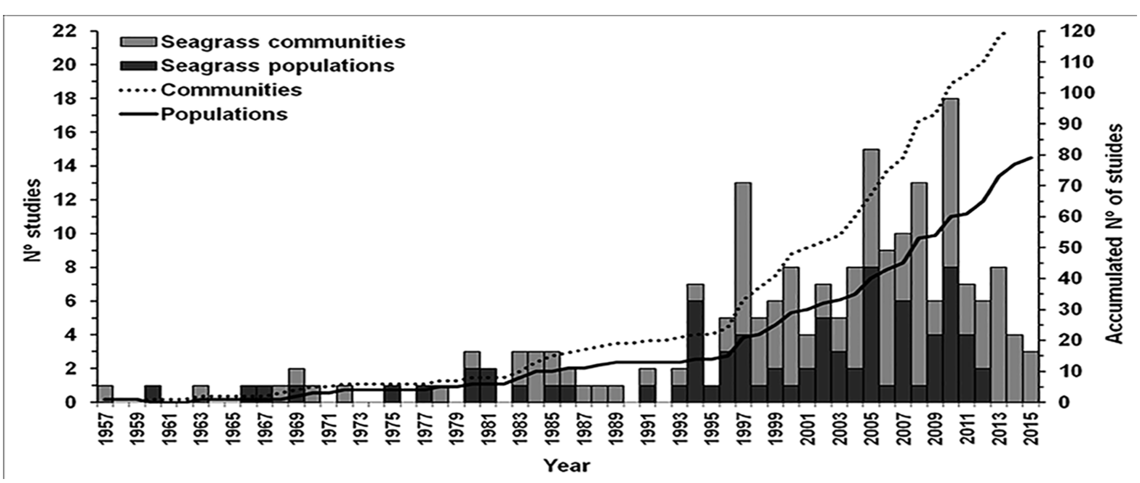

Figure 2. Number of yearly publications (articles, thesis, dissertations, book chapters) containing information about Brazilian seagrass habitats, accounting for studies that include only seagrass species (populations, black columns) and the studies which include the associated flora and/or fauna (communities, grey columns), since the first published studies in 1957.

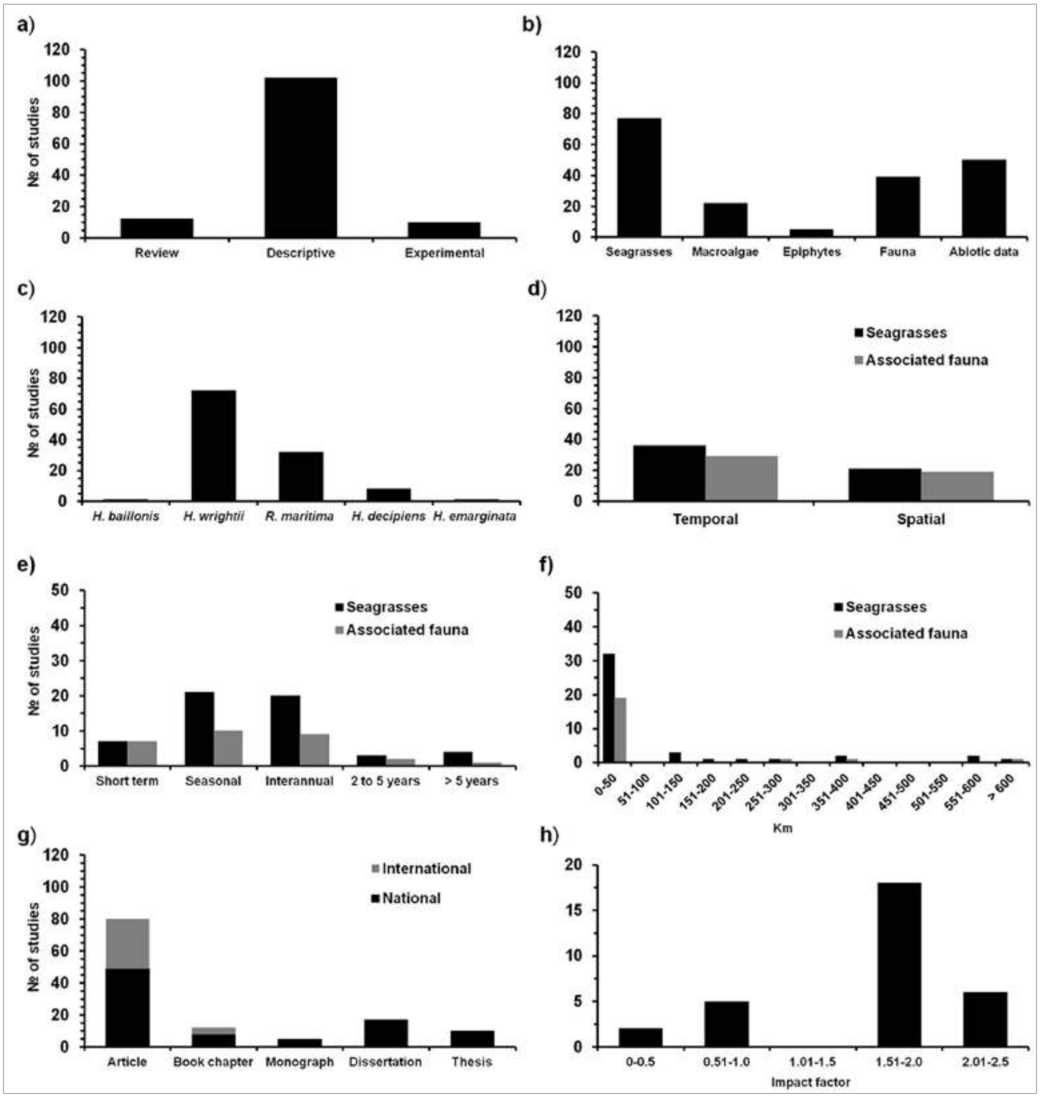

Figure 3. Scientometric analysis of Brazilian seagrass publications according to different criteria. Studies were classified according to their (a) methodological approach, (b) studied taxonomical/ecological groups and (c) target seagrass species. Few studies analyzed (d) temporal and spatial variability, which were performed at different (e) temporal and (f) spatial scales. The number of studies per (g) publication source and (h) the journal impact factor of the international articles are given.

between seasons or wet-dry seasons) and interannual (1-2 year) studies of the plants dominate (Figure 3e). Short-term (a few months), seasonal and interannual studies are also the most common for seagrass-associated fauna. Most studies are local or of a small scale (0-50 km) (Figure 3f).

Approximately half of the retrieved references are peer-reviewed articles, the remainder being distributed among book chapters, theses, dissertations and monographs (Figure 3g). Most peer-reviewed articles have been published in indexed national journals. Less than half of the peer-reviewed articles were published in international journals with impact factors varying between 1.51 and 2.5 (Figure 3h).

This current scenario shows that despite the increase in the number of studies, communication of the results is still relatively limited and mainly addressed to a national or regional public. The predominance of descriptive, local and short-term studies provides basic knowledge of the composition and structure of submerged angiosperm prairies in Brazil. However, the scarcity of large-scale and long-term studies, which would allow the detection of changes in the structure, abundance and composition of seagrass habitats and associated species, still hinders the investigation of such communities with respect to the potential effects of climate change.

Species occurrence and distribution

Seagrasses (sub-class Alismatidae) are distributed among five major family groups: Zosteraceae, Posidoniaceae, Cymodoceaceae (all species in these groups are seagrasses), Hydrocharitaceae (with 3 true seagrasses), Ruppiaceae and Zanichellaceae (these last two contain true and euryhaline seagrasses) (WAYCOTT et al., 2002). Compared with terrestrial plants and macroalgae, seagrasses present low diversity, with approximately 12 genera and more than 60 species (DEN HARTOG; KUO, 2006). Including the euryhaline species, the authors counted 76 species distributed across 15 genera.

Although eleven species of seagrasses are currently reported for the Tropical Atlantic (SHORT et al., 2010), the consensus is that only five occur along the Brazilian coast, as follows: *Halophila baillonis* Ascherson, *Halophila decipiens* Ostenfeld (Hydrocharitaceae), *Halodule wrightii* Ascherson, *Halodule emarginata* Hartog (Cymodoceaceae) and *Ruppia maritima* Linnaeus (Ruppiaceae) (OLIVEIRA et al., 1983; CREED, 2003) (Figure 4). *Ruppia maritima* has the widest distribution, ranging from Maranhão State (2º S) to Rio Grande do Sul State (33º S), but it is confined to shallow areas (20 cm to 3 m depth) in estuaries, coastal lagoons, fishponds, mangrove areas, salt marshes and salt ponds, growing under conditions from low salinity to hypersaline.

Halodule is associated with shallow habitats (less than 10 m depth) with little freshwater input, such as reefs, macroalgal beds, coastal lagoons, sandy beaches and soft-bottom areas and nearby mangrove areas with little salinity fluctuation. *H. wrightii* has the widest distribution along the marine coastline, ranging from the states of Piauí (2º S) to Santa Catarina (27º S) (OLIVEIRA et al., 1983; FERREIRA et al., 2014). The occurrences in the Santa Catarina state have only recently been reported, suggesting a possible poleward expansion of this tropical species (FERREIRA et al., 2014). Being a widespread tropical species, with a high light requirement, *H. wrightii* is more abundant in Northeast Brazil, where average temperatures are higher. In Southern Brazil the species reaches the limit of its distribution at Florianópolis, occurring in small patches with reduced biomass, and to date, in one shallow estuarine system. The reduction in abundance results from changes in density and morphometric parameters. These changes in abundance are also observed to depend on wave exposition and sediment stability. *H. emarginata* is restricted to the tropical region between Ceará (3° 49' S) and São Paulo (23° 45') (OLIVEIRA et al., 1983). The taxonomy of *H. emarginata* (supposedly a species endemic to Brazil) is uncertain, and there are many doubts about the validation of this taxon. This species is identified mainly by its biometric characteristics, especially the leaf tips, but genetic studies are still needed (BARROS et al., 2013).

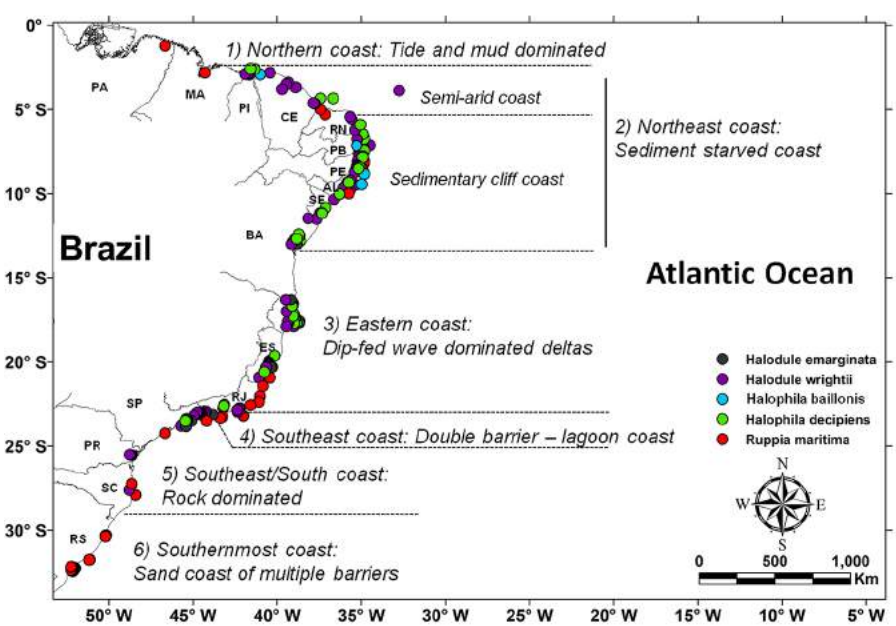

Figure 4. Distribution of the seagrass habitats and species along the coast of Brazil based upon all the existent records, in each coastal compartment. The coastal compartments were classified and characterized by DOMINGUEZ (2009) and MUEHE (2010), according to geomorphological, oceanographic and hydrological aspects.

Halophila decipiens is restricted to the tropical region associated with riverbanks, deeper and shallow reefs, macroalgal and maerl beds and deeper, soft-bottom, vegetated areas. Having a more delicate form with less-developed rhizomes, the species is more suited to calm waters. The lower light requirement allows this species to occur at depths down to 85 m (DEN HARTOG, 1970). *H. baillonis* was registered in 1980 and 1988 in the state of Pernambuco, (surrounding Santa Cruz Channel, 9° 45' S) (DEN HARTOG, 1972; OLIVEIRA et al. 1983), but it was not found again for at least three decades (BARROS et al., 2013). Recently, the species has been reported on the northeastern coast of Brazil, between Piauí (Cajueiro da Praia, 2° 55' S) and Paraíba (Barra de Mamanguape, 6° 47' S), with at least two areas of well-established beds (BARROS et al., 2014; MAGALHÃES et al., 2015).

Coastal geomorphology and seagrass habitat distribution

The Brazilian coast extends for 9,200 km (islands not included) from 4° N to 33° S with a very diverse suite of a coastal environments that evolved during the Quaternary period in response to changes in climate and sea level (DOMINGUEZ, 2009). Brazil has one of the world's most extensive river systems, with eight major drainage basins, all of which drain into the Atlantic Ocean. It rains all year round along the coastal zone, with the exception of northern Brazil where up to six dry months are observed (DOMINGUEZ, 2009). The tidal range progressively increases from south (< 1 m) to north (> 6 m) (SALLES et al., 2000). The major mechanisms of wave formation are intrinsically associated with the cold fronts, and the trade winds and wave heights average 1-2 m with periods of 5-7 s. Because of these different mechanisms of wave formation, the central portion of the Brazilian coastline is subjected to two competing wave systems: east-northeastern and south-southeastern waves, with important implications for sediment dispersal (DOMINGUEZ et al., 2006).

The interaction of the geological background, sea level history, sediment supply, present climate (temperature, wind speed and precipitation) and associated oceanographic processes (waves and coastal currents) has contributed to the development of the different landscapes along the Brazilian coastline (DOMINGUEZ, 2009). There is a great variety of environments such as macrotidal plains covered by mangrove forests in the north; semi-arid coasts, bordered by Tertiary cliffs and delta-like coastal plains on the central coast; and wave-dominated environments in the south, either characterized by dissipative beaches at the border of the Late Quaternary coastal plain or rocky shores and eventually interrupted by reflective-to-intermediate pocket beaches (DOMINGUEZ, 2009; MUEHE, 2010; DIAS et al., 2012). Based on these relatively unique characteristics, the major coastal typologies or compartments present in Brazil have been described by DOMINGUEZ (2009) and MUEHE (2010).

Seagrass meadows and SAV occur all along the Brazilian coast (Figures 4 and 5), but species distribution, abundance and dynamics are affected by physical drivers, particularly the coastal geomorphology, oceanography and regional climate and hydrology. Based on the assumption that these factors are good predictors of seagrass distribution and abundances, we used DOMINGUEZ's (2009) coastal typologies and MUEHE's (2010) coastal compartments to characterize the Brazilian seagrasses (Figure 4). For this, we used the published and unpublished (personal communications and our own data) information about the dominant species and their abundances (cover, densities and biomass), depth of occurrence and associated flora and fauna. This approach is also useful for predicting the vulnerabilities of Brazilian seagrasses to climate change because each of those coastal compartments are exposed to different types and levels of impacts (MUEHE, 2010).

1) The Northern coast: tide and mud-dominated

The northern Brazilian Coast (1,200 km long) receives the largest volume of sediment on the entire coast of Brazil because of the Amazon River and other associated rivers (e.g., Tocantins and Parnaíba; DOMINGUEZ, 2009). It has a wide continental shelf (up to 300 km wide) and is controlled by macrotidal processes (> 4 m, up to 6.3 within estuaries), with wide estuary mouths and short and narrow barriers (SOUZA-FILHO et al., 2009). The region holds the largest mangrove system in the world and the gorge of the largest river in length, water and sediment discharge, the Amazon River (SOUZA-FILHO, 2005). It has a tide-mud-dominated coast to the west (Amapá-Guyanas) and a tide-dominated mangrove coast to the east (Pará-Maranhão) (DOMINGUEZ, 2004). No seagrass meadows have yet been registered on the shore or within the large estuaries. We believe that the combined effects of very high fluvial discharge, mud deposition, turbid waters and macrotidal regime make the coastal region highly unsuitable for the establishment of seagrass meadows. However, there are

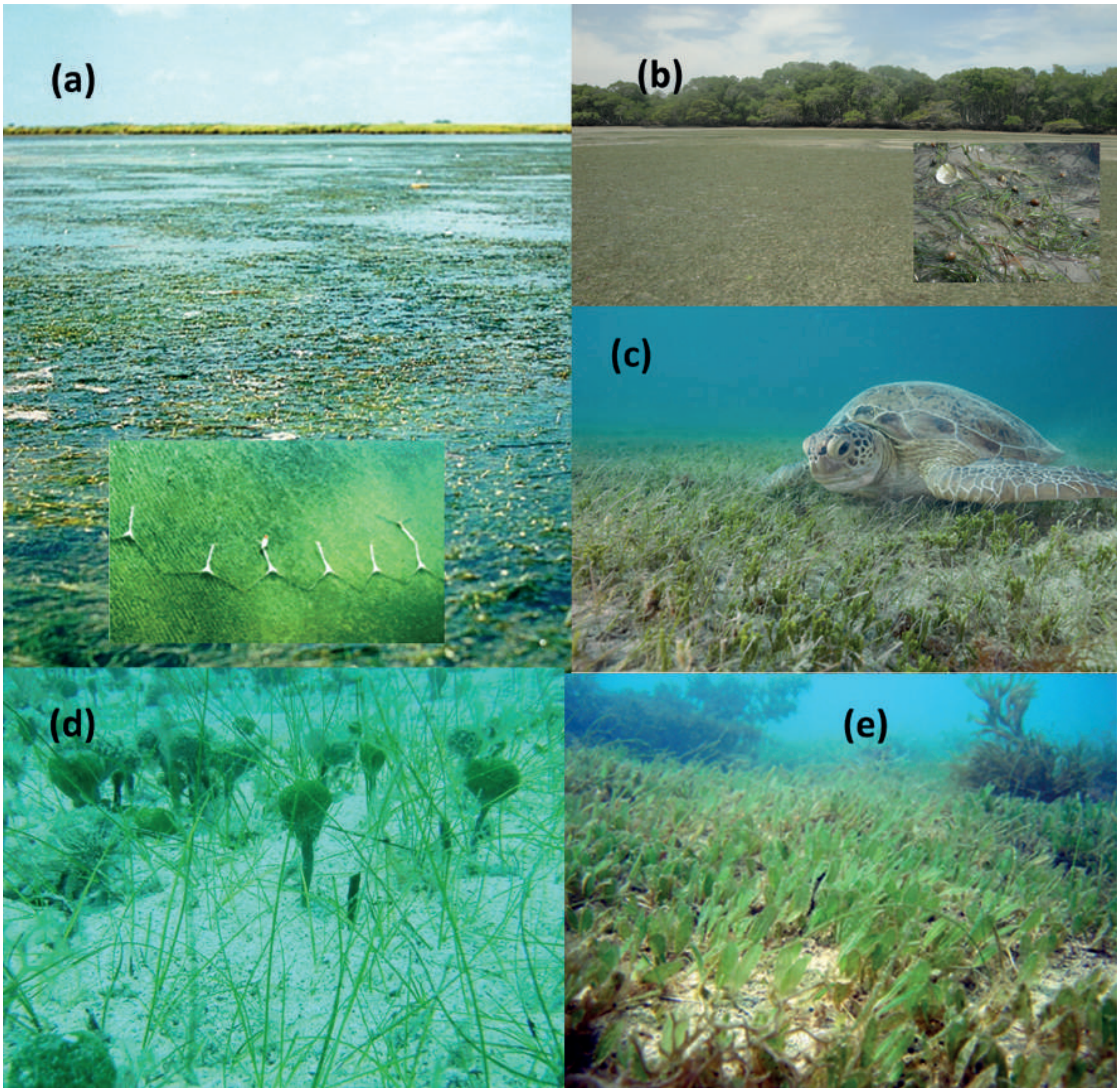

Figure 5. Seagrass habitats and species. a) Meadows of *Ruppia maritima* in very shallow areas (< 1.0 m) of Patos Lagoon estuary (RS), with salt marshes at the back. The insert shows an aerial view of shrimp fishing nets ("rede de aviãozinho") fixed on vegetated bottoms. b) Intertidal meadows of *Halodule* sp in Macapá River estuary (Parnaíba Delta, PI) during low tide, with mangroves at the back. c) Green turtle (*Chelonya mydas*) resting on mixed seagrass-macroalgae stands in Abrolhos National Park (BA). d) Stands of *Halodule wrigthii* and calcareous macroalgae (*Penicillius*) growing on calcareous sand bottom. e) Deep meadows of *Halophila decipiens* surrounding coral reefs in Abrolhos National Park (BA). Image credits: U. Seeliger (a), M. S. Copertino (b), Luciano Candisani (c) and J. C. Creed (d,e).

some scarce meadows dominated by *R. maritima* confined to enclosed lagoons and water bodies, isolated from the sea or temporarily connected to it by narrow channels called igarapés (Lagoa da Jensen in Maranhão, CASTRO et al., 2015; Salina dos Roques in Pará, U. MEHLIG, Per. Com.)

2) The Northeast coast: sediment starved

The northeastern region of Brazil is a sediment-starved coastal zone, resulting from low relief, small drainage basins and a semiarid climate (DOMINGUEZ, 2009; MUEHE, 2010). The coast is dominated by sedimentary cliffs (Barreiras group), the river runoff is extremely low and the whole area suffers from coastal erosion. The coastline is characterized by the presence of actively retreating cliffs, beachrocks (cemented upper shoreface sediments) and coral-algal reefs built on top of the beach rocks and abrasion terraces (DOMINGUEZ; BITTENCOURT, 1996).

The northwestern section of the region is a semi-arid coast (Piauí, Ceará and the west coast of Rio Grande do Norte), very dry and highly impacted by erosion (MUEHE, 2010). Seagrasses are relatively abundant in the region, dominated by *H. wrightii* meadows and restricted to intertidal and shallow subtidal areas along rocky (sandstone) shores and inside estuaries and lagoons.

The eastern section of the northeast coast, from south of Rio Grande do Norte to northern Bahia, has a more humid climate (MUEHE, 2010). It includes a barrier reef coast that stretches intermittently for 3,000 km (between Pernambuco and Bahia States) and comprises coral and sandstone barrier reefs that act like breakwaters, decreasing the wave energy and limiting sediment re-suspension to the shore. The calm and very clear waters formed in the inner shelf lagoons provide the ideal environmental conditions for the development of seagrasses in dense meadows. Therefore the northeast region holds seagrass hotspots, and plant distribution and abundances are lower northward and southward of this region. The juxtaposition of coral fringing reefs and the shoal complex formed by the Todos-os-Santos Bay (the second largest bay in the country covering approximately 1,200 km²), Itaparica Island, Morro de São Paulo, Boipeba and Camamu Bay contain extensive seagrass meadows of *Halodule* and deeper water populations of *H. decipiens*, few of which are known.

3) The Eastern coast: dip-fed wave dominated deltas

The eastern coast (in Bahia, Espírito Santo and Rio de Janeiro) receives a considerable volume of sediment as a result of the presence of large rivers draining high-relief, humid areas (DOMINGUEZ, 2009). The presence of the sedimentary cliffs is still dominant but less continuous in the southern part. The region is marked by alternations in dominance between the waves generated by the trade winds and the swell waves generated by cold fronts from the south, and it is highly susceptible to the changes in dominance between tropical and subtropical climatic-oceanographic processes (MUEHE, 2010). The coast alternates among regions of equilibrium, accretion and erosion, with more than 30% of the coastal area suffering from erosion, and accretion occurring mainly on the coastal plains of the river delta (DOMINGUEZ, 2009; MUEHE, 2010).

The presence of seagrasses in this region appears to be a trade-off between depth and turbidity. Because waters are turbid due to wave action and river discharge, seagrass meadows occur sporadically, mainly in the following three situations: 1) as sparse intertidal populations, where beach sand is sufficiently stable on the leeward side of beachrock reefs or on the reefs in rock pools with sandy bottoms; 2) as denser intertidal populations on a smaller rock shore forming embayments or estuaries (e.g., Santa Cruz, ES) or in larger subtidal bays where waters are less turbid (e.g., Victoria Bay); and 3) as intertidal-shallow subtidal populations in lagoons (*R. maritima*) (Southern Espírito Santo). In this compartment, meadows are found in slightly deeper waters further offshore, between the protective reefs, down to at least 20 m and between deeper reef pinnacles called chapeirões. The largest coral reef banks in the South Atlantic occur in this region (Abrolhos Bank), but the high sediment suspension nearshore prevents seagrass growth. Rhodoliths and calcareous and rhizophytic macroalgae are associated with meadows. South of the Abrolhos bank, extensive sandy beaches occur with beachrock reefs exposed at low tide.

4) The Southeast coast: double barrier-lagoon

This compartment, along the Rio de Janeiro State coast, has an almost east-west alignment to the coastline, being highly exposed to storm waves from the south (MUEHE, 2010). The longshore sediment transport tends to be in equilibrium throughout the year, with the less frequent, high-energy waves (swell) from the south and southwest being compensated for by the more frequent waves from the southeast. Strong wave action on the sandy beaches is not conducive to seagrass colonization. The meadows are restricted to channels, bays and lagoon estuaries (e.g. *R. maritima* in the urban Marapendi and Rodrigo de Freitas Lagoons; *R. maritima* and *H. wrightii* in the Itajuru Channel, Araruama lagoon) or as smaller populations on a rocky shore forming embayments in the Lakes region (*H. wrightii*) and within the Guanabara Bay (*H. decipiens*).

5) The Southeast and South rocky coast

From the Ilha Grande Bay (Rio de Janeiro State) to the Santa Marta Cape (Santa Catarina State), the coast is characterized by the proximity of the coastal mountain range (Serra do Mar), resulting in a submerged landscape with a sequence of high cliffs, innumerous small coves and beaches interconnected by rocky shores (DOMINGUEZ, 2009; MUEHE, 2010). From São Vicente to northern Santa

Catarina, including the coast of Paraná, the coastline is formed by long beaches and wide coastal plains with wide estuaries, such as at Santos and Cananéia in São Paulo, Paranaguá and Guaratuba in Paraná and São Francisco do Sul in Santa Catarina. From northern Santa Catarina to southern Santa Catarina Island, the coastline becomes irregular with outcrops of the crystalline basement and small coastal plains.

Along this coastal region, the intertidal and shallow rocky shores and reefs are dominated by macroalgal beds, whereas seagrass meadows (mainly *Halodule*) occur on very shallow sandy bottoms or within coastal lagoons. In São Paulo, *H. wrightii* and *H. decipiens*, are observed in patches, with reduced biomass, within bays and channels. In Santa Catarina these environments were not observed in open waters. The occurrence in this area is restricted to shallow coastal lagoons and estuaries, where *Ruppia* and more recently *Halodule* have been listed.

6) The Southern coast: sandy multiple barrier

From Santa Marta Cape (Santa Catarina) to Chuí (Rio Grande do Sul) on the border between Brazil and Uruguay, the coastline is formed by a long, wide, fine-grained and continuous beach in front of a multiple barrier-lagoon system, the widest lagoons being the Patos and Mirim Lagoons (MUEHE, 2010). The series of barriers are separated by low-lying areas occupied by freshwater wetlands and large fresh-water bodies, with no access to the sea but for the Rio Grande, Tramandaí and Chuy inlets (TOMAZELLI et al., 2000). This is the longest barrier system in South America and certainly one of the longest in the world (DILLENBURG et al., 2009). The sediment supply to build this large coastal plain came from La Plata River (the second largest river system in South America) with the contribution of local rivers (Camaquã and Jacuí) (DOMINGUEZ, 2009). The direct exposure to the oceanic swell and the high frequency of storm-generated waves submit the shoreline to a harsh wave climate. The coast is a typical wave-dominated coast with a combination of moderate-to-high wave energy and a very low microtidal regime (0.5 m) (DILLENBURG et al., 2009). The high wave energy and sediment instability together with the high turbidity have prevented the establishment of seagrass meadows at the shore until the present day. However, seagrasses and SAV, dominated by mixed stands of *R. maritima*, oligohaline plants (*Zannichellia palustris*, *Potamogeton striatus*) and green macroalgae dominate the coastal lagoons and estuaries (e.g., Patos Lagoon, the Tramandaí-Armazém Complex, Lagoa do Peixe). Ephemeral meadows can occur over great extensions in these very shallow waters (from a few cm up to 3 m depth), mainly in summer periods.

The sites studied: the knowledge of seagrasses in each coastal region

Northeast

The most representative and dense seagrass meadows in Brazil are concentrated on the northeast coast (OLIVEIRA et al., 1983; MAGALHÃES et al., 1997; MAGALHÃES et al., 2003; FRANÇA et al., 2013) mainly in the Timonha-Ubatuba Estuarine System (PI), at Camocim, Acaraú, Icapuí (CE), Tamandaré, Itamaracá (PE), on the Abrolhos Bank and Morro de São Paulo (BA) (MAGALHÃES; ESKINAZI-LEÇA, 2000; MAGALHÃES; ALVES, 2002; MAGALHÃES; CAZUZA, 2005; BARROS ET AL,. 2014). Two estuarine complexes of extreme biological importance are located on the border of Ceará and Piauí (BARROS,; COSTA; ROCHA-BARREIRA, 2015). In addition to being home to established endangered species such as the manatee, they are breakpoints and feeding grounds for migratory birds. The areas include the largest remaining mangrove forest in northeastern Brazil (except for that in Maranhão state) with an area of more than 10000 hectares. The Timonha-Ubatuba Estuarine System, located between the states of Piauí and Ceará, holds the most diverse seagrass meadow found anywhere on the Brazilian coast, where the species *Halodule* sp., *H. wrightii*, *H. baillonis* and *H. decipiens* (BARROS et al., 2014) occur together.

Fishing is the main economic activity of many coastal communities in northeastern Brazil (IDEMA, 1999; IBAMA, 2006), including fisheries for organisms such as lobsters and shrimps with life cycles related to the seagrasses. There are reports of the economic dependence of fishermen in areas with high fishing production where dense areas of seagrass meadows are found -according to the records in Ceará State (IDEMA, 1999) and also in the Santa Cruz Channel and on Itamaracá Island (Pernambuco State) where 5000 fishermen depend on the fisheries (LIMA; QUINAMO, 2000). Coral fishing, the main sea fishing activity in the northeast region (PAIVA; NOMURA, 1965), is still frequently found in the meadows of *H. wrightii* in the intertidal zone, and is practised especially by subsistence fishermen or small-scale producers.

Goiabeiras Beach (Ceará State). In the semi-arid sector of the Northeast, seagrass meadows are well estabilished on beach rocks. On Goiabeiras Beach, the *H. wrightii* meadow has a variable shape of approximately 30 m in length (BARROS; ROCHA-BARREIRA, 2014) with an associated macrofauna comprising 29 crustacean species, 27 molluscan species and 16 families of polychaetes in addition to the ectoprocts and hydrozoans attached to the leaves and cerianthids, nemerteans, oligochaetes and ophiuroids, with amphipods being most abundant aboveground and polychaetes belowground (BARROS, 2008; BARROS; ROCHA-BARREIRA, 2010; 2013). The associated macrofauna, both aboveground (shoots) and 10 cm into the sediment, is strongly influenced by the local hydrodynamics. The species do not have a distinct vertical distribution because some species are found both aboveground and belowground (BARROS; ROCHA-BARREIRA, 2010; BARROS; ROCHA-BARREIRA, 2013).

In addition to the features of the substrate on which the seagrass meadow has become established (i.e., rocky and sandy habitats), which strongly influence the biology of the meadows and associated flora and fauna (BARROS et al., 2013), the pronounced seasonality of rainfall and the wind patterns in this region have been related to the variation in the vegetative characters of *H. wrightii*, for which patterns should be monitored for future evaluations related to the influence of climate changes on the meadows of this region (BARROS; ROCHA-BARREIRA; MAGALHÃES, 2013; BARROS; ROCHA-BARREIRA, 2014).

H. wrightii meadows have a higher homogeneity in cover percentage and greater canopy height and biomass during the rainy season, probably due to the increase in fine and organic matter percentages in the sediment (BARROS; ROCHA-BARREIRA, 2013; BARROS; ROCHA-BARREIRA, 2014). During the dry season, the meadows are reduced to smaller patches, and some leaves are burnt. The waves, influenced by the increase in wind velocity, remove fine sand and provide an input of medium-coarse sand into the meadows as well as dislodging mature leaves. Despite this, the shoot density in the patches increases during the dry season, promoting retention and increase in diversity of flora and fauna in the meadows (BARROS; ROCHA-BARREIRA, 2013; BARROS et al., 2013).

Barrier Reef Coast (Pernambuco and Alagoas State). The eastern sector of the Northeast has the most representative and abundant seagrass meadows in Brazil (MAGALHÃES et al., 1997; MAGALHÃES et al., 2003). The region possesses one of the largest marine protected area in Brazil (400,000 ha), APA "Costa dos Corais", a polygon that stretches across 120 km of the coastal zone (and 30 km offshore), covers parts of the states of Pernambuco and Alagoas (ICMBio, 2012). The area was created to protect the unique and interconnected coral reefs, seagrass meadows and mangrove systems, with their endemic and endangered species (e.g., the manatee *Trichechus manatus*).

Seagrass meadows have been recorded at at least 20 sites along the coast of Pernambuco, which includes beaches, coastal lagoons, and estuaries (MAGALHÃES; CAZUZA, 2005) and on the oceanic island, Fernando de Noronha (CREED, 2003). Along the coast of Paraíba, Pernambuco and Alagoas, *H. wrightii* meadows are found from the intertidal zone to a depth of 10 m and are established mainly in areas protected by beach rocks or coral reefs on both soft and hard substrates (KEMPF, 1970; LABOREL-DEGUEN, 1963; FRANÇA et al., 2014). *H. decipiens* is generally found in association with *H. wrightii*, but in calm and protected areas with muddy sediment between 30 cm and 40 m depth (KEMPF, 1970; LABOREL-DEGUEN, 1963). *H. baillonis* occurs together with *H. wrightii* and *H. decipiens* in areas protected by reefs with strong turbidity and up to 3 m depth (MAGALHÃES et al., 2015). *R. maritima* meadows are found in estuarine areas, of which the Olho d'Água Lagoon in Recife, Pernambuco, where the sediment is muddy and has a high percentage of organic matter, is a good example (COELHO, 1965; MAGALHÃES; CAZUZA, 2004).

A rich fauna comprising mollusks and crustaceans is associated with *H. wrightii*, including especially amphipods, gastropods, isopods and decapods in addition to sea cucumbers and chordates (ALVES, 2000; MAGALHÃES; ALVES, 2002). The meadows are frequently used as nurseries by the peneids *Farfantepenaeus brasiliensis* and *F. subtilis*, for which greater abundance occurs during the rainy season and within the meadow area relative to adjacent non-vegetated areas (F. VIANA, pers. comm.). At Tamandaré Beach, Pernambuco, the meadows are established on calcareous sediment derived from fragments of *Halimeda* sp. and corals. These meadows have a well-defined seasonality, with significantly greater biomass and density during the dry season (SHORT et al., 2006).

Abrolhos Bank. The Abrolhos Bank is situated in the south of the Bahia state, on a widening (to approximately 200 km) of the Brazilian continental shelf that occurs in the southwest Atlantic Ocean between 17 and 20°S. The tropical region is mainly influenced by the Brazilian Current; it is responsible for the high temperatures of the surface seawater and contains the largest mesophotic reefs in the southern Atlantic as well as rhodolith beds and unconsolidated sediments (LEÃO et al., 2013). The Abrolhos Archipelago, which comprises five small islands with small fringing reefs, is located 65 km off the southern coast of Bahia state, Brazil, and is part of a marine protected area, the Abrolhos Marine National Park (LEÃO; KIKUCHI, 2001). The shallow, soft-bottomed marine communities near the coral reefs of the Abrolhos archipelago are dominated by macrophytes comprising algae and the seagrasses *Halodule wrightii* and *Halophila decipiens* (CREED; AMADO, 1999; DE PAULA et al., 2003).

Despite the considerable research interest invested in the Abrolhos Marine National Park, seagrasses have been overlooked and were not reported until the year 2000 (CREED; AMADO, 1999). Monitoring only began in 2002 using the SeagrassNet Global Seagrass Monitoring Program Protocol (SHORT et al., 2005), and it showed that, in fact, *H. wrightii* and especially *H. decipiens* were probably more common than previously believed. *H. wrightii* is found in shallow sandy areas interspersed with coastal reefs and around the Abrolhos Archipelago while *H. decipiens* is found at a depth of at least 22 m. The suspicion that *H. decipiens* might be very abundant on the Abrolhos Bank was confirmed during a Rapid Assessment Protocol of biodiversity conducted in the region (DUTRA et al., 2006). Of the 45 reef edge/soft-bottom sites selected, *Halophila* was present at 18 (40%) of them. Although no total area quantification was made, these sites were distributed over a study area of approximately 6,000 km^2; thus, the potential importance of *H. decipiens* in the region, especially in terms of primary productivity, could be enormous. Large vertebrates, such as sea chub, parrotfish, surgeonfish (FERREIRA; GONÇALVES, 2006) and green turtles graze intensively on the seagrass and 56 associated seaweed species. Between 5% and 12% of the stomach content of herbivourous fishes (*Kyphosus* spp. 12%, *Acanthurus chirurgus* 8 %, *Sparisoma* and *Scarus* 0.5-5 %) are composed of seagrasses (FERREIRA; GONÇALVES, 2006). *Chelonia mydas* has been observed grazing on *H. wrightii* meadows, taking 32 bites per minute (J.C. CREED, unpublished data)

Southeast

Seagrass beds occur sporadically throughout the states of Espirito Santo, Rio de Janeiro and São Paulo where suitable conditions for seagrass development: shallow unconsolidated substrate, wave-protected position and suitable water quality, are available. Seagrasses are therefore limited to embayments, the leeward side of islands and some estuaries and lagoons. While many studies have been published on the seagrass biology and ecology of the Rio de Janeiro coast (see MARQUES; CREED, 2008 for a review), almost nothing is known about seagrasses in Espirito Santo and São Paulo States other than some distributional observations (OLIVEIRA et al., 1983). Despite the observed decreased biomass and densities (J.C. CREED, unpublished data), there is no published systematic characterization of the community structure or population dynamic of the seagrass beds in these coastal regions. In 2013, as part of an ongoing National Seagrass Mapping Project, 80 sites in Espírito Santo State were visited, and seagrasses were found at 14 points (J.C. CREED, unpublished data). Similarly, on the better known northern coast of Rio de Janeiro, 9 sites visited yielded 6 new recordings (J.C. CREED unpublished data). In São Paulo, seagrasses were registered at about 12 sites (most shallow beaches) during the 80s (OLIVEIRA et al., 1983). The sites were revisited in 2014 and meadows were found in only three of them (P. HORTA, unpublished data). In addition, new subtidal meadows have been recorded (D. GORMAN, unpublished data).

Araruama Lagoon (Rio de Janeiro State). The *H. wrightii* beds in Rio de Janeiro that were listed by OLIVEIRA et al. in 1983 were revisited ten years later, and 16% of the seagrass beds were found to have been lost (CREED, 2003). In contrast, according to CREED (2000a), a search for seagrass meadows in the state yielded 12 (of 28) as previously unreported. The authors conclude from these observations that 1) little is known about seagrasses in Rio de Janeiro and 2) we are losing some of what we have. To redress this situation, the Universidade do Estado do Rio de Janeiro (UERJ) initiated a seagrass monitoring program at Araruama Lagoon in Cabo Frio. Monitoring has been conducted seasonally (January, April, July and October) from spring 1995 to the present, following protocols including the SeagrassNet Global Seagrass Monitoring Program (SHORT et al., 2005). The monitoring site is situated on the Ilha do Japonês (22º 52.951’ S; 42º 00.168’ W) in the Itajuru channel which links the Araruama Lagoon to the sea. The lagoon is hypersaline, with salinity varying from 35 to 40 and temperature from 17 to 32.5 ºC. The lowest spring tides occur during the day from April to October, and the tidal range is 1.4 m. The area is subject to a bi-directional tidal flow in and out of the lagoon and is protected from wind and waves (CREED, 1997; CREED, 1999). These site features create a unique oceanographic settling. Seagrass meadows comprising *H. wrightii* and some *R. maritima* extend from the intertidal to shallow subtidal zone. Aspects of the short-term temporal dynamics and morphology of the seagrass bed have already been described by CREED (1997, 1999). In addition to the seagrasses, macroalgae, mainly *Jania adhaerens* J.V. Lamour., *Hypnea* spp. and *Acanthophora spicifera* (Vahl) Børgesen, are abundant. The cerith *Cerithium atratum* (BORN, 1778) is the most highly abundant (mean density 1887.m^{-2}) and ecologically important gastropod within the seagrass meadow (CREED, 2000b). Fish, shrimp and blue crab from the seagrass beds are commercially exploited. Over the ten-year period, the average seagrass canopy height showed a consistent decline followed by a recovery. The shoot density was more dynamic (MARQUES et al., 2015). These data show that the dynamics of seagrass change at Cabo Frio are complex and apparently contain multiple cyclic influences. This type of data will be extremely useful in ongoing investigations assessing climate change and its effect on seagrasses in Brazil.

South

Paranaguá Bay (Parana State). *Halodule wrightii* meadows occur on shallow subtidal sandy bottoms in the euhaline high-energy sector of Paranaguá Bay, a well-preserved subtropical estuarine system in southern Brazil. Near their southernmost limit in the South Atlantic, local populations are patchy, unstable and infrequently sexually reproductive. SORDO et al. (2011) assessed the seasonal morphological and biomass variations of a local *H. wrightii* meadow on Rasa da Cotinga Island from a healthy state to its subsequent decline and die-off. The leaf width and length, the number of leaves per shoot, leaf sheath length, rhizome width, internodal length and biomass, together with sediment grain size and $CaCO_3$ and POM contents were measured on six occasions between November 2004 and October 2005. Compared with other *Halodule* meadows along the Atlantic coast, local plants had shorter and narrower leaves, shorter leaf sheaths, thinner rhizomes, a lower number of leaves per shoot, and higher internodal distances. The highest values for all plant variables were found in the summer. There was an important decrease in shoot density and in below- and above-ground biomass, with the clearance of the internal areas of the meadow, in colder months (June 2005). This started a marked decline in the extent and biomass of the local meadow, which had totally disappeared by the beginning of 2006. It has been suggested that such marked temporal variations in morphology and plant biomass, which may lead to local meadow regression and disappearance, are a latitudinal pattern to be expected. The dynamic appearance and disappearance of seagrass meadows in Paranaguá Bay, which seem to follow a regular and somewhat predictable pattern, are related to the fact that this species is locally close to its southernmost distribution limit. Because of its great adaptability as a pioneer and short-lived species, *H. wrightii* can grow and reproduce vegetatively under stressful conditions such as high turbidity and lower salinities and temperatures. This study also suggests that the increase in spatial differences in plant cover and abundance in a seagrass meadow is an early indicator of future regressions and can be used in monitoring evaluation and/or stress identification programs. The seagrass meadows in Paranaguá Bay have been studied since 2004 (SORDO, 2008), and the steady decline of at least two seagrass meadows has been observed at Rasa da Cotinga Island, accompanying a worldwide trend. The first meadow (25° 32' 31.8" S; 48° 24' 04.3" W) was found in 2004, and had completely disappeared by the beginning of 2006. This decline was attributed to a number of overlapping stress factors, such as low temperatures and higher turbidity levels associated with cold fronts (SORDO et al., 2011). Two months later a new meadow (25° 31' 51. 6" S; 48° 23' 47.5' 'W) appeared in the same area. To identify reliable and consistent proxies of the early stages of seagrass decline for conservation purposes, SORDO and LANA (unpublished data) compared the benthic fluxes in the sediment and water column and the responses of plant and macrobenthic variables as between the two meadows from December 2006 until the complete regression of the Rasa da Cotinga meadow by the beginning of 2008 following an overgrowth of the epiphytic brown algae *Hincksia mitchelliae* (Harvey) P. C. SILVA. The differences between sites increased with the progressive degradation of the Rasa da Cotinga meadow. With an unexpected boost of epiphytic biomass, plant growth was suppressed and the numbers of burrowing and opportunistic macrobenthic species increased. In the healthy meadow, seagrass biomass and the number of leaves followed the usual seasonal trends, and macrobenthic abundance and species richness remained stable with no evident changes in species composition. The nutrient fluxes at the sediment-water interface were highly inconsistent between and within sites and sampling periods and did not reflect the evident changes in plant and animal variables. The algal overgrowth, together with an increase in the abundance of annelid and crustacean bioturbators only affected oxygen production positively in the advanced stages of seagrass decline. This study showed that plants and animals, rather than the benthic fluxes or nutrient concentrations at the sediment-water interface, were the first and most reliable indicators of the early stages of seagrass decline. Changes in the number of leaves per shoot, abundance and composition of the macrofaunal associations and the host-epiphyte surface interactions could be monitored to detect such changes in regression events. The use of these early warning bioindicators may contribute to more effective management measures for the monitoring and conservation of seagrass ecosystems.

To characterize the type of epiphytism occurring between *H. mitchelliae* and its host plant, PAPINI et al. (2011) compared two samples at the beginning and end of the algal overgrowth by means of electron and optical microscopes. The presence of plasmodesmata between the cells of *H. mitchelliae* only in the late stage of the host-epiphyte interaction indicated a change in the vegetative organization of the algae in relation to its host to improve nutrient absorption and distribution through the epiphyte cells. *H. mitchelliae* and other epiphytes adhered to the surface of *Halodule* causing shadowing and the disruption of the osmoregulatory system of the plant. The authors concluded that in the late stage of epiphytism, algal epiphytes led to the death of the seagrasses. The surface interaction between the epiphyte and its host plant may be considered an indicator of seagrass health and could be integrated into monitoring programs for the management of seagrass ecosystems (PAPINI et al., 2011).

Patos Lagoon Estuary (Rio Grande do Sul State). On the extreme southern Brazilian coast, seagrasses live under such extreme and variable environmental conditions that they present the lowest diversity and sparsest distribution on the southeastern Atlantic Coast. With a coastline dominated by exposed sandy beaches and high wave energy, SAV (composed by *R. maritima*, oligohaline, fresh-water grasses and eurihaline macroalgae) in Rio Grande do Sul State is restricted to enclosed estuaries and coastal lagoons (e.g. Tramandaí-Armazém Estuarine Complex, Lagoa do Peixe and Patos Lagoon Estuary.

The largest is Patos Lagoon, the most extensive choked lagoon in the world (KJERFVE, 1986). The system has a high ecological significance and sustains several social-economical activities (fisheries, agriculture, aquiculture, port and tourism) (ODEBRECHT et al., 2010).

Nearly 175 km^2 of shallow estuarine areas (70% of the Patos Lagoon estuary) provides suitable conditions for the settlement and development of SAV, composed mainly *R. maritima* meadows (COSTA et al., 1997; SEELIGER et al., 1997a). These vegetated areas are used as nurseries and habitats by important marine and estuarine fishing resources such as pink shrimp (*Farfantepenaeus paulensis*), blue crab (*Callinectes sapidus*), mullet (*Mugil platensis*), bluefish, catfish and whitemouth croaker (*Micropogonias furnieri*) (D'INCAO, 1991; GARCIA et al., 1996; GARCIA; VIEIRA, 1997; ASMUS, 1989; COSTA et al., 2015; RUAS et al., 2014), which sustain a local economy involving more than 6000 artisanal and 3000 industrial fishermen (REIS, 1992; HAIMOVICI et al., 1997; KALIKOSKI; VASCONCELOS, 2012). A recent study of fisheries management and conservation in Patos Lagoon concluded that the local vegetated shallow bottoms are essential fish habitats that should be preserved as no-take zones (COSTA et al., 2015).

Fluvial discharge and winds are the driving forces behind the Patos Lagoon's hydrology, whereas the influence of the low tide (~ 0.4 m) is limited to the estuary mouth (MÖLLER et al., 2010). The average annual salinity is low (10-15 ppt), but salinity is highly variable throughout the year (0-35 ppt) and between years (ODEBRECHT et al., 2010). Therefore, the shoals (< 2.0 m) are temporally covered by *R. maritima*, the most tolerant and eurihaline of seagrass species, *Zannichellia palustris* (oligohaline) and drift macroalgal species (mainly *Ulva clathrata, U. flexuosa, U. intestinalis*, *Cladophora* spp, *Rhizoclonium riparium*, *Polysiphonia subtilissima*) (CAFRUNI et al., 1978; SEELIGER et al., 1997b). *Ruppia maritima* leaves and stems hold significant biomasses of epiphyte algae (FERREIRA; SEELIGER, 1985), together with the unattached green macroalgae (SILVA, 1995).

Spatial and seasonal variability of seagrass abundance and distribution, accounting for water column and sediment parameters, have already been described (COSTA; SEELIGER, 1989; COSTA et al., 1997; SILVA; ASMUS, 2001), and an ecological model of biomass production has been developed as a function of water depth and transparency (SILVA; ASMUS, 2001). The development of seagrass meadows in the Patos Lagoon, their variability and the equilibrium among plant and algal populations are highly dependent on hydrodynamics, particularly on the critical initial stages (COPERTINO; SEELIGER, 2010). When water and sediment movements are moderate (usually in late spring and throughout the summer), light, temperature and salinity enhance the growth rates, biomass allocation and flower production (KOCH; SEELIGER, 1988; COSTA; SEELIGER, 1989; SILVA; ASMUS, 2001; COLARES; SEELIGER, 2006). Due to this synergistic effect, seagrass growth is concentrated in the spring and summer with meadows decaying or disappearing in the winter. Although a high spatial and temporal variability is intrinsic to the local populations, drastic reductions in abundance (3 times lower biomass compared with the values found in the 1980s and 1990s) and distribution (more than 50%) were observed between the end of the 1990s and the beginning of the 2000s, causing extreme habitat fragmentation and changes in community structure (COPERTINO, 2010; COPERTINO; SEELIGER, 2010; ODEBRECHT et al., 2010). The changes, including sudden disappearance from more exposed areas, were strongly correlated with precipitation anomalies and extreme events (storms and wind generated waves), some of them associated with ENSO episodes. Within these periods (e.g., 1997/1998, 2001/2003), precipitation anomalies occurred in southern Brazil and were reflected in increases in the Patos Lagoon's fluvial discharge (MÖLLER et al., 2009). The higher discharge and anomalous flows increased the average estuarine water level and turbidity, reduced salinity and enhanced sediment movement in the shallow areas. A single extreme event (October 2001) driven by a synergistic effect of high fluvial discharge and prevailing strong winds quickly raised the estuarine water level, dislodging salt marsh areas and several seagrass meadows. The responses of the *R. maritima* population to the unfavorable conditions were relatively rapid, but complete recovery was a slow process (~10 years in some areas). A reduction in seed bank and germination rates appeared to reduce the chances of the formation of meadows (CORDAZZO, 2004). As a result of habitat fragmentation, the few shoots or seedlings were highly vulnerable to even moderate water and sediment movement, thus inhibiting meadow formation.

The conservation status and main threats

Seagrasses and submerged aquatic vegetation (SAV) have been suffering major changes and losses in abundance, community structure and functions for the last 40 years, most notably from the worldwide deterioration of water quality (ORTH et al., 2006; BURKHOLDER et al., 2007; WAYCOTT et al., 2009). The causes of the rapid seagrass decline during the last decades of the last century are mainly attributed to the increasing impacts associated with anthropogenic activities such as the occupation of the coastal zone, eutrophication, overfishing, dredging and pollution (SILBERSTEIN et al., 1986; SHEPHERD et al., 1989; PERGENT-MARTINI; PERGENT, 1996; BURKHOLDER et al., 2007). On the other hand, fast and significant losses have also been linked to extreme natural events such as coastal erosion, abnormally high temperatures, storms, cyclones, precipitation extremes, drought and desiccation (PREEN et al., 1995; SHORT; WYLLIE-ECHEVERIA, 1996; SEDDON et al., 2000; SEDDON; CHESHIRE, 2001), many of which are predicted to increase in frequency and intensity in several coastal areas in response to global climate change (TRENBERTH et al., 2007; BINDOFF et al., 2007). Furthermore, the observed and predicted changes in water CO_2 concentrations, temperature and sea level may potentially affect the physiology, abundance and structure of seagrass communities (DUARTE, 2002). All of these factors together, i.e., environmental degradation and global climate changes, will certainly impact the structure and functioning of these submerged vegetated habitats.

Anthropogenic impacts along the Brazilian coast: a historical perspective

In general, the gradual and slow worldwide decline of seagrass meadows has been attributed to anthropogenic impacts such as eutrophication, runoff of nutrients and sediments, aquaculture, destructive fishing practices and pollution (SBERSTEIN et al., 1986; SHEPHERD et al., 1989; PERGENT-MARTINI; PERGENT, 1996; BURKHOLDER et al., 2007; BJÖRK et al., 2008). With an average population density of 22 inhabitants/km^2, the level of anthropization in Brazil is less evident than it is in European and American countries; however, it is highly concentrated in metropolitan coastal areas.

As a consequence of historical processes, Brazilian coastal areas have been substantially altered over recent centuries (DIAS et al., 2012). Since the arrival of the first Europeans, human populations have been established mostly in estuarine areas (e.g., Salvador, Rio de Janeiro, Santos, Iguape, Paranaguá, and Porto Alegre). The settlement of the Portuguese Royalty in Brazil (1808), together with Independence (1822), promoted an increase in the size and activity of harbors (expansion, dredging, inlet fixation, breakwaters, jetties) and urban growth along the shores, and the former city-ports became large cities. From 1940 on, mining activities (iron and steel industries) along with other industrial activities demanded significant changes in the major ports of Santos (SP), Rio de Janeiro (RJ), Paranaguá (PR) and Vitória (ES). Consequently, pollution became a problem within areas such as Guanabara Bay (RJ) and the estuaries of Sao Paulo state (BAPTISTA NETO et al., 2013). Since the middle of the 20th century, a tourist boom has also been affecting the Brazilian coast. Multiple resorts have been constructed, promoting urban development in cities such as Fortaleza (PAULA et al., 2013), Recife (COSTA et al., 2008), Balneário Camboriú (COSTA et al., 2006), and Santos (MELLO, 2008), among others. As a result of all of these anthropogenic impacts, the Brazilian coast has been suffering from erosion, land reclamation and pollution problems, and the degree of deterioration has been increasing still further in recent years (GALVÃO; NOLASCO, 2013; SOUSA et al., 2013).

Within this context, historical and published records of seagrass losses across Brazil are scarce. By comparing historical observations and studies (of the 1970s and 1980s) with recent monitoring and experimental studies (of the 1990s and 2000s), major seagrass changes and losses (up to 50% losses) have been detected, mainly surrounding metropolitan areas such as Recife (SHORT et al., 2006; MAGALHÃES; ALVES, 2002; PITANGA, 2012), Rio de Janeiro, Búzios, Cabo Frio (CREED, 2000a; CREED, 2003), Santos Bay (E. C. OLIVEIRA, Pers. Comm.) and Patos Lagoon Estuary (COPERTINO, 2010; COPERTINO; SEELIGER, 2010; ODEBRECHT et al., 2010). The effects of anthropogenic impacts on each coastal region may interact with regional features such as wind regime, hydrology and oceanographic and coastal morphology. Brazilian seagrass meadows have thus been exposed to different anthropogenic impacts of varying intensity, and they may be vulnerable to different stresses according to climate and coastal dynamics and ecosystem resiliencies.

In the northeast region, anthropogenic and natural impacts on seagrasses have been qualified and quantified along the Pernambuco coast, indicating significant changes in the meadows' extension and abundances (PITANGA et al., 2012). The losses have been attributed to impacts such as continental discharge, urban development, boating activity, destructive fishing techniques and the dumping of solid waste (PITANGA et al., 2012). While some losses have been attributed to natural causes or extreme events (SHORT et al., 2006), many meadows have been reduced due to seagrass harvesting to feed captive manatees (MAGALHÃES; ALVES, 2002). The local media and fishing community have attributed the decline in fishery production to shoal grass (*H. wrightii*) losses. Similarly, the construction of the coastal breakwaters and artificial structures around Fortaleza (Ceará State) has resulted in high levels of coastal erosion associated with greater exposure to wave energy and ocean storms (PAULA et al., 2013). Seagrass habitats in this coastal region are, therefore, highly vulnerable to increases in wave impacts, sediment erosion and burial. Insights into anthropogenic impacts have also come from the Abrolhos Marine Protected Area. Despite being within a marine protected area, the seagrass meadows in the Abrolhos National Park lose 0.5 percent of their area per year due to anchor damage (CREED; AMADO, 1999). The observed reductions in seagrass density and the changes in the community structure can require more than a year to recover after a single impact.

The southeastern region is probably the most impacted coastal area in Brazil. It has been subjected to successive phases of land disturbance since the sixteenth century as a consequence of widespread urbanization (BAPTISTA NETO et al., 2013a). In common with most of the humid tropics, the Southeast Coastal Range is subject to an extremely erosive climatic regime characterized by periods of prolonged and frequently intense rainfall (BAPTISTA NETO et al., 2013a), which increases continental runoff into the Rio de Janeiro, São Paulo and Espirito Santo coastal regions. The opening of coastal inlets in the Cananéia region (São Paulo) has brought about changes in hydrodynamics, including a decrease in salinity, an increase in turbidity and further changes in geomorphology and sedimentation patterns (MAHIQUES et al., 2009). Several organic geochemical indicators suggest that the changes in sediment organic matter reflect the alteration of the processes of the occupation and urbanization which have been occurring in the areas surrounding metropolitan waters over the last 70 years. These processes have included the conversion of mangrove forests into urban areas, bridge building and the installation of treatment plants (GRILLO et al., 2013; BAPTISTA NETO et al., 2013a). In and surrounding Guanabara Bay, for example, the catchment area has been greatly modified by human activities over the last 100 years, in particular by the deforestation and uncontrolled settlemen, which have generally increased the river discharges and sediment loads flowing into the bay (BAPTISTA NETO et al., 2013b). Consequently, the average rates of sedimentation are very high (from 0.67 cm y^{-1} to 2 cm y^{-1}) compared with other less impacted environments in southeastern Brazil. The concentration of heavy metals has shown a constant increase over the last 50 years, related to an increase in urbanization (post-1950) and deforestation (pre-1950) in the catchment area. The same pattern was also observed for the organic carbon flux, which could indicate the recent impact of the dumping of untreated sewage into the bay. The high levels of estuarine sediment contamination by organic compounds and heavy metals are typical of highly urbanized and industrialized estuaries around the world. Along the São Paulo coast, the spread and low density of seagrass meadows in the shallow subtidal zone, exposed to a high variability in water turbidity, have decreased during the last several decades (E. OLIVEIRA, Pers. Com.). The *H. wrightii* beds listed by OLIVEIRA et al. (1983) were revisited ten years later and 16% of them were found to have been lost (CREED, 2003).

In the extreme southern region of Brazil, a long-term study of the Patos Lagoon Estuary has proved fundamental to the understanding of the complexity of and environmental responses to natural and anthropogenic impacts (SEELIGER; ODEBECHT, 2010; ODEBRECHT et al., 2010). Human impacts such as the construction of jetties, the dredging of navigation channels, sediment removal and resuspension and the input of domestic and industrial effluents, have led to profound changes in the ecology of the Patos Lagoon Estuary. Among them, seagrass coverage and abundance have been reduced by more than 50% since the 80s (COPERTINO, 2010; COPERTINO; SEELIGER, 2010). The expansion of aquatic plant species with low tolerance to high salinity (COSTA et al., 2003; MARANGONI; COSTA, 2009) and the marked reduction of the area and abundance of seagrass meadows (COPERTINO; SEELIGER, 2010) cannot be explained solely by changes in hydrology. Increases in frequency and abundance of opportunistic macroalgae and the formation of large green tides have been registered (GIANASI et al., 2011; LANARI; COPERTINO, under review) at the same time that eutrophication processes have been detected (ABREU et al., 2006).

Climate Variability and Global Climate Change

Climate change is predicted to profoundly impact marine biodiversity and ecosystems by changing the functioning, behavior, and productivity of organisms, leading to shifts in the size, structure, spatial range, and seasonal abundance of populations (DONEY et al., 2012). The first studies on the effects of climate changes on seagrasses and SAV were comprehensive reviews, extrapolating information from physiological and ecological studies to assess the potential impacts of global climate change on seagrasses (SHORT; NECKLES, 1999; DUARTE, 2002). Of more than 1,400 articles found on seagrasses and SAV, only 416 (~3%) are related to climate change factors and issues (Web of Knowledge, March 6, 2015). A growing number of studies attribute the worldwide changes in seagrasses to climate variability and global climate change (UNSWORTH, 2014), although most have only mentioned or contextualized climate change problems in their introductions and final discussion. Many studies are observational, with climate change effects being extrapolated from mid-long term temporal series or from the plant/meadow responses to extreme events such as hotter summers, hurricanes, anomalous runoff, droughts and so on (e.g., CARLSON et al., 2010). During the last decade, few studies have tested working hypotheses or investigated particular climate change effects through design experiments (e.g., UNSWORTH et al., 2012; COLLIER; WAYCOTT, 2014; GARTHWIN et al., 2014; YAAKUB et al., 2014) or produced prognoses based upon IPCC climate scenarios and modelling (SAUNDERS et al., 2014).

The expected impacts of climate change on oceans and coastal areas that will potentially affect seagrasses and other submerged aquatic vegetation are manifold (Table 1). For instance, it is expected that the increasing rate of global climate change with the associated increases in temperature and carbon dioxide will impact the redistribution of current seagrass habitats. Differences between species in their ability to compete for CO_2 could lead to enhanced competition between algae and seagrasses, shifting the species distribution (SHORT; NECKLES, 1999). Nonetheless, few authors have provided empirical evidence linking the observed changes in seagrass populations to climate change with a reasonable level of confidence. Firstly, the lack of continuous data series makes it impossible to find indications of long-term changes in abiotic and biological parameters. Even for the few long-term series, it is hard to separate the evidence of the changes in global climate (such as temperature increase) on the regional and local scales due to high natural variability and, particularly, the impacts of other anthropogenic activities.

Table 1. Predicted climate change impacts and their hypothetical effects on seagrass and SAV meadows and associated species.

Impact	Effects on seagrass meadows
Warming (air and sea surface temperature)	Changes in species geographic distribution and reproduction timing
Increases in Nutrient Load	Increases in the abundance of epiphyte algae and opportunistic macroalgae; changes in species composition; appearance of toxic algae
Sea level rise/increases in wave energy	Changes in lower and upper limits (meadow range); reductions in abundances
Changes in salinity	Physiological stress; changes in leaf and shoot morphology
Increases in turbidity	Reduction in primary production and meadow abundance
Increases in pCO_2/Acidification	Changes in photossyntetic response/reduction in calcification rates of associated calcareous macroalgae and shellfish
Extremes events (floods, storm surge)	Meadow burial, fragmentation and disappearance

In Brazil, losses on the Tamandaré Beach (Pernambuco) have been related to the increasing frequency and intensity of storms in 2003, which increased the transport of sediments, acting on the distribution and biomass of *H. wrightii* (SHORT et al., 2006). On the semi-arid coast, the intertidal seagrass meadows are strongly influenced by rain and wind patterns, and, consequently, they may be drastically affected by the effects of climate change related to the diminishing of precipitation indexes (REBOUÇAS, 2004) and the doubling of the actual windy velocity (PEREIRA et al., 2013), expected by the end of this century.

Ecological assessments at the biogeographical limits of distribution may also provide important insights for predicting shifts in seagrass range in response to climate change and ocean acidification. During the 80s, the southernmost *H. wrightii* meadows were recorded at 23^o 55' S, around Santos (São Paulo State). In the late early 2000s, *H. wrightii* meadows were found at 25^o 30' S, in Paranaguá Bay (Paraná State) (SORDO et al., 2011). A recent study on sporadic *H. wrightii* meadows has suggested that, at its southernmost distribution limit, their survival depends on their degree of exposure (SORDO; LANA, unpublished data). In protected and preserved areas the plant communities are stable and could be extending their distribution. In 2012, almost ten years later, a *H. wrightii* prairie was found further south, at 27^o 35' S, in Florianópolis (Santa Catarina State), which is permanently epiphytized by the macroalgae *Hincksia* and *Polysiphonia*, and disappears cyclically every summer. The events described above, in particularly the recent appearance of the species in Florianópolis, raise the hypothesis that the species may be extending its distribution poleward. Although this shift in the latitudinal limits may be a response to global warming, the projected increases in average sea temperature and CO_2 levels may also stimulate the proliferation of opportunistic algal species which outcompete seagrasses for light, space and nutrient resources. Consequently, the survival and widening of the range of *H. wrightii* at its southernmost geographical limit in the southwestern Atlantic may be related not only to the degree of exposure but also to its ability to compete with ephemeral macroalgal species. Despite the registered evidences that the tropical seagrass *H. wrightii* is extending its distribution further south, we still lack a proper ecological assessment along the southwestern Atlantic coast, which could include experimental studies and a species distribution model, in order to better understand the effect of temperature and CO_2 increases on the distribution of seagrass species.

In the Patos Lagoon estuary in southern Brazil, the relationship between climatic/hydrological parameters and the distribution and abundance of estuarine SAV have been analyzed for a period of 30 years (COPERTINO, 2010; COPERTINO; SEELIGER, 2010; ODEBREHT et al., 2010). Although they present high seasonal and interannual variability, both seagrasses and macroalgae suffered drastic reductions between the mid-1990s and beginning of this century (1996 to 2004). ENSO episodes, which appear to have increased in frequency during the last several decades, were inversely related to the abundance of SAV by altering precipitation patterns and causing extreme discharges through the estuary. The first significant biomass reduction was observed in 1996, and just before the year 2000, meadows were gradually reduced. In 2002 and 2003, *R. maritima* meadows disappeared completely from most estuarine areas after extreme precipitation and fluvial discharges, with values (~5000 m^{-2} s^{-1}) three times larger than the annual means (MÖLLER et al., 2009). The rise in estuarine water levels during this period caused erosion on salt marsh margins, which lost between 40% and 100% of their intertidal habitats (MARANGONI, 2008), transporting high amounts of sediment and plant material to adjacent submersed areas. The tendency of freshwater runoff to increase is thought to be caused by the increased precipitation over southern South America (MÖLLER et al., 2009), which has experiencied a warmer and wetter period during recent decades (GARREAUD et al., 2009); nevertheless, changes in land use (deforestation, urbanization) may also be involved. After El Niño periods, there are drops in river flow and water level, resulting in increases in light availability to benthic primary producers. However, in the absence of seagrasses, the bare bottoms can be fast occupied by opportunistic algae, characterizing phase-shifts to macrolgal dominated states (COPERTINO; SEELIGER, 2010). Dry periods, associated with lower wind stress, promote low water renewal, the maintenance of high algal biomasses and the recycling of organic matter within the shoals, potencially triggering the overgrowth of macroalgae and the formation of green tides (LANARI; COPERTINO, under review). During summer periods, the rapidly growing algae can cover between 70% and 100% of shallow areas, with biomass values compared to those found in eutrophicated estuaries (FLINDT et al., 1997; MARTINS; MARQUES, 2002).

Although the seagrass decline occurred relatively fast, the recovery process took more than 10 years, relying on a reduced seed bank, low germination rates and the high dependence on favorable water conditions and sediment stability. High macroalgal biomass interferes with the recovery of the seagrass meadows, by reducing light at the bottom and because of the effects of the toxic compounds released from decay. The fast biomass decay causing anaerobic conditions at the sediment surface, may be responsible for collapses of the benthic infauna (CUMMINGS et al., 2004). The shift from a seagrass-dominated to a drift-algae-dominated state may impose ecological consequences such as the reduction of stable habitats for invertebrates and fishes, some of which are important local fishing resources.

The above studies and results can have important implications for the prediction of the impacts of climate change on the coastal ecosystem and seagrass habitats of Brazil. Climate change projections over South America show an increase in wet-season precipitation and a decrease in dry-season precipitation over most of the continent (MARENGO et al., 2009; KOCH et al., 2011). Precipitation intensity is greatest over southern South America in the present-day simulation and in the future, implying increased river flow and an increased risk of flooding in this region (MILLY et al., 2005; KOCH et al., 2011). Southern South America is one of the extratropical regions most affected by the ENSO regime, and southern Brazil is the region with the clearest reflections of El Niño, marked by warmer periods and precipitation anomalies (GRIM et al., 2000). Projections of anthropogenic climate change models indicate an increase in the frequency of ENSO episodes in the near future (TIMMERMAN et al., 1999; FEDOROV; PHILANDER, 2000; YEH et al., 2009). If all of these predicted tendencies are proven correct, the conservation of seagrass habitats and the estuarine ecosystems in Southern Brazil may be at risk. Experimental and modeling studies are still necessary to enable us to draw conclusions about past and future tendencies in the abundance and distribution of seagrasses in the Southwestern Atlantic, including past investigations on a larger spatial scale.

CONCLUSIONS

The current conservation status of Brazilian seagrasses and SAV is critical. We still rank a decade or two behind the more scientifically developed centers in terms of quantitative information or process-focused research. The unsustainable exploitation and occupation of coastal areas (DIAS et al., 2012) and the manifold anthropogenic footprints left during the last 100 years (TESSLER et al., 2006; MAHIQUES et al., 2009) have led to the loss and degradation of shoreline habitats potentially suitable for seagrass occupation surrounding coral or sand reefs, bays, coastal lagoons and estuarine shoals. Despite this worrisome status and trends of decline, South American seagrass formations are rarely included or cited in global reviews or ecological models.

Knowledge of the prevailing patterns and processes governing seagrass structure and functioning along the 9000 km Brazilian coast is sorely needed for the global discussion on climate changes. Our review is a first and much needed step toward a more integrated and inclusive approach to the diversity of coastal plant formations along the Southwestern Atlantic coast. It is also a regional alert to the projected or predicted effects of global changes on the goods and services provided by regional seagrasses and SAV.

Future studies must be planned and designed to incorporate spatial and temporal variation into multiscale, nested approaches. Assessing the effects of climate change on regional seagrasses will also require continuous and long-term monitoring. The systematic implementation of impact assessment and monitoring protocols will be necessary for a better understanding of the largescale and longterm relative importance of environmental drivers on seagrass resources and services. Such integrated approaches are particularly needed in the regions under higher human pressure and are thus more vulnerable to the projected changes in climate. In addition to the description and quantification of still-unknown meadow areas, experimental approaches (especially in long-term studies) are still much needed in Brazil. By addressing spatial and temporal variations in multiscale approaches and by developing experimental protocols, the Brazilian scientific community will be able to better address the extent and implications of projected changes and the associated fluctuations in carbon stock.

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Benthic estuarine communities in Brazil: moving forward to long term studies to assess climate change impacts

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Abstract

Estuaries are unique coastal ecosystems that sustain and provide essential ecological services for mankind. Estuarine ecosystems include a variety of habitats with their own sediment-fauna dynamics, all of them globally undergoing alteration or threatened by human activities. Mangrove forests, saltmarshes, tidal flats and other confined estuarine systems are under increasing stress due to human activities leading to habitat and species loss. Combined changes in estuarine hydromorphology and in climate pose severe threats to estuarine ecosystems on a global scale. The ReBentos network is the first integrated attempt in Brazil to monitor estuarine changes in the long term to detect and assess the effects of global warming. This paper is an initial effort of ReBentos to review current knowledge on benthic estuarine ecology in Brazil. We herein present and synthesize all published work on Brazilian estuaries that has focused on the description of benthic communities and related ecological processes. We then use current data on Brazilian estuaries and present recommendations for future studies to address climate change effects, suggesting trends for possible future research and stressing the need for long-term datasets and international partnerships.

Descriptors: Estuaries, Benthic ecology, Climate change, Brazil, Impacts

Resumo

Estuários são ecossistemas costeiros que sustentam uma ampla variedade de serviços ambientais para a humanidade. Estuários abrigam muitos ambientes bentônicos com características específicas e seriamente ameaçados globalmente. Manguezais, marismas e planícies de maré são amplamente impactados por poluentes domésticos e industriais, por atividades comerciais que levam à perda de *habitat* e pela sobrepesca. Os diversos impactos locais, associados a mudanças regionais e globais na hidromorfologia estuarina e potenciais efeitos de mudanças climáticas, colocam sérias ameaças a ecossistemas estuarinos. A rede Bentos foi criada para estudar o efeito de mudanças no clima em ecossistemas bentônicos costeiros brasileiros. Este trabalho faz parte dos esforços iniciais do Grupo de Trabalho Estuários em rever o conhecimento sobre comunidades bentônicas estuarinas no Brasil. Aqui apresentamos uma breve revisão crítica sobre os trabalhos realizados objetivando o estudo, em nível de comunidades, do bentos estuarino e processos ecológicos associados. A partir do cenário atual, realizamos recomendações de estudo para responder questões científicas sobre efeitos de mudanças climáticas em comunidades bentônicas estuarinas, e enfatizamos a necessidade de bases de dados contínuas e de longa duração e o estabelecimento de parcerias internacionais com foco específico nos estuários brasileiros.

Descritores: Estuários, Ecologia bêntica, Mudança climática, Brasil, Impactos

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INTRODUCTION

Estuarine benthic ecosystems are heterogeneous systems that provide highly diverse habitats and their biological assemblages are frequently used as indicators of natural and anthropogenic changes. The spatial and temporal variability of estuarine populations and communities are largely conditioned by climate, run-off regimes and oceanic dynamics, through changes in nutrients, primary production and sediments (MALLIN et al., 1993; HEIP et al., 1995). Thus estuarine fauna must be highly adapted to deterministic and stochastic environmental changes (ELLIOTT and QUINTINO, 2007) which may occur on a local, regional or global scale. Local and regional changes may be linked to the relative dominance of riverine, wave or tidal processes directly affecting habitat diversity and spatial and temporal gradients in sediments and organic matter.

Brazil has a long coastline with over one hundred estuaries from the tropical equator in the North to due to regions in the South. Brazilian estuaries differ widely in their tidal regimes (e.g. from macrotidal on the northern to microtidal on the southeastern and southern coasts), input of run-off discharges (i.e., higher average rainfall in the northern and southern regions) and wave action. Geomorphological differences are also main causes of dissimilarities among Brazilian estuaries (DOMINGUEZ, 2006). Estuaries dominated by riverine inputs are more frequent in the N and NE and within bays, and drowned estuaries and lagoons are more common in the SE and S. Macroscale changes associated with large-scale environmental differences in Brazilian estuaries may be due to atmospheric, oceanographic and climate variability, as well as to local or regional human activities. Global climate dynamics could, therefore, act directly upon local estuarine benthic populations or promote cross-scale interactions influencing species responses on both local and regional scales.

Estuaries have been intensely modified over recent decades by human activities. Sewage outfalls and eutrophication, habitat loss, overfishing and several hydrodynamic changes have produced marked impacts worldwide (NORKKO et al., 2002; SCAVIA et al., 2002). Brazilian estuaries are no exception and several studies have reported multiple human impacts near large urban areas (SANTI and TAVARES, 2009; SOARES-GOMES et al., 2012; KRULL et al., 2014). It is widely accepted that potential effects of climate change will further impact estuarine communities by changes in average temperature, in yearly rainfall and in mean sea level (ATTRILL and POWER, 2000; NAJJAR et al., 2000; GILLANDERS and KINGSFORD, 2002). However, it is still extremely difficult to predict the intensity and scale of these changes and the response of biological communities and changes in ecosystem functioning. Temperature and rainfall anomalies, as well as sea level rise, have been commonly reported across the globe and these effects may have substantial impacts on estuarine ecosystems over both the short- and long-term (ALONGI, 2008; DAY et al., 2008; CONDIE et al., 2012; TURRA et al., 2013; GARCÍA-RODRIGUEZ ET AL., 2014). For example, if regional and local rainfall anomalies and sea level changes alter the salt balance of an estuary, it might cause changes in species distribution and productivity (THURMAN et al., 2010; CONDIE et al., 2012). Higher temperatures could also affect the metabolism, growth and reproduction of estuarine biota, which combined with local eutrophication may lead to oxygen depletion and mass mortality of organisms (BISHOP et al., 2006). It is expected that the intensity of impacts and ecological effects of climate change on estuaries will be site-specific. However, long-term changes in climate may also alter estuarine communities and ecosystem resilience on larger scales that are relevant to ecosystem management and function (DOLBETH et al., 2011; ELLIOTT and WHITFIELD, 2011; MCLEOD et al., 2011).

Projected changes in global climate are the greatest current threat to ecological function and the associated socio-economic services provided to mankind (ANTLE et al., 2001; DONEY et al., 2012; TURRA et al., 2013). As such, the major challenge to modern ecology is to understand and to predict how climate change will translate into ecological impacts and affect human well-being. To scientifically assess changes in estuarine ecosystems and promote their long-term conservation and management, we have created “The Monitoring Network for Coastal Benthic Habitats” (ReBentos - Working group on Estuaries), an integrated effort on the part of researchers and institutions along Brazil’s 8,000 km of coast line. ReBentos’s main goals are to establish long-term observations of benthic estuarine communities and other coastal ecosystems, through sound scientific practices to detect and assess the effects of climate change. The ReBentos Estuaries working group’s assignment is to develop studies using the estuarine benthic fauna as a biological model for climate change assessment. Benthic ecosystems are particularly useful to understand how estuaries will be affected by climate change because they are the key to many biogeochemical and ecological processes at the sediment water interface (SMITH et al., 2000; KRISTENSEN et al., 2008). Benthic communities are also overwhelmingly used as indicators of the biotic quality of estuarine ecosystems, and thus the ReBentos project's efforts qualify it for inclusion among several international programs with similar goals (e.g. Climate Ready Estuaries - EPA/USA; Marbef network program - EU).

In order to design and propose a long-term monitoring program, we have carried out an exhaustive synthesis of published work on the benthic communities of estuarine ecosystems in Brazil and have assessed their vulnerability to past and current changes in temperature and rainfall (BERNARDINO et al., 2015a). These theoretical predictions may be useful to address site-specific vulnerabilities in several Brazilian estuaries to projected climate change and result in mitigation and adaptation on a regional scale. The ReBentos network has proposed several protocols to standardize historical time series data acquisition on benthic estuarine ecosystems across Brazil. In order to suggest best scientific practices for long-term monitoring of benthic ecosystems, this paper: i) critically reviews the published work on estuarine benthic invertebrates along the Brazilian coast in respect to their usefulness as baselines for climate change studies; ii) suggests a long-term sampling protocol using benthic communities as models for climate-related impacts in estuaries, and iii) compares the ReBentos Estuaries protocol with current international strategies with similar objectives.

MATERIAL AND METHODS

A review of all work published in peer-reviewed and indexed journals up to and including 2012 was made by means of the Web of Science®, SCOPUS and Google Scholar. Benthic compartments, including meiofauna, macrofauna and megafauna, were selected after satisfying the basic criterion of focusing on community ecology. Taxonomic surveys and other specific work on benthic fauna were not included in this review but can be found elsewhere (LANA et al., 1996). Selected papers were classified according to 1) region (N, NE, SE and S), 2) habitat (mangrove forest, saltmarsh, unvegetated sediments), 3) tidal position (subtidal or intertidal), and 4) sampling interval (months to years and number of sampling events during the study).

RESULTS

A total of 50 published papers on the benthic estuarine communities of 48 different estuaries were found (Table 1). These papers cover roughly three decades of study - from 1986 to 2012, with sampling efforts concentrated in the more developed areas of southern and southeastern Brazil (ca. 75% of published papers; Figure 1). Despite the greater number of studies of estuaries from the southeastern and southern regions, most published works were concentrated on a few sites (Figure 1). The Northeastern region had a higher number of estuaries studied than did the Northern region, although both had generally a lower number of studies published (Figure 1). The sampling effort was greater in a few estuaries in the S and SE. For example, the estuarine systems of Guanabara Bay (RJ), Cananéia (SP), Paranaguá Bay (PR) and Patos Lagoon (RS) were intensely studied in respect to their benthic fauna and ecosystem dynamics (Table 1). On the other hand, most estuaries were investigated in respect to their community description on local to regional scales and only at a few sites were studies of a more general nature (e.g. community succession, pollution effects, trophic interactions) or where in situ experimentation been carried out included.

Benthic macrofaunal communities in subtidal channels and on intertidal flats were the most studied estuarine habitats along the Brazilian coast (Figure 1). Macrofaunal communities in saltmarshes (*Spartina*) were mainly studied on the northern and southern coasts in Pará, Santa Catarina, Paraná and Rio Grande do Sul (Figure 1). Megafaunal communities were mostly studied in mangrove forests and on hard substrates, with some efforts made in subtidal estuarine channels in some areas. On the eastern and southeastern coasts, macrofaunal and megafaunal communities were investigated in the polluted urban areas of the Pernambuco coast, Vitoria (ES), Guanabara (RJ) and Santos (SP). Benthic communities in mangrove forests and, saltmarshes and tidal flats were also studied in a few preserved areas of Rio de Janeiro and São Paulo in the southeast (Table 1). Significant sampling efforts on intertidal communities of unvegetated flats, saltmarshes and mangrove sediments were carried out in estuaries on the southern coast. In general, epifaunal communities in mangrove forests and *Spartina* marshes and on rocky substrates at specific sites were little studied.

Most benthic estuarine studies in Brazil have focused either on the description of patterns of community

Table 1. Summary of selected published papers on the benthic ecology of Brazilian estuaries from 1986 to 2012.

Area	State	Estuarine Habitats	Site	Depth	Sampling interval	Benthic fauna	Reference
Pará, Northern Brazil	PA	Tidal flat	Caeté estuary	Intertidal	2 days	Macrofauna	ROSA FILHO et al., 2006
	PA	Saltmarsh (*Spartina*)	Eight estuaries along Pará coast	Intertidal	1 year, 4 sampling events	Macrofauna	BRAGA et al., 2011
	PA	Mangrove	Caeté estuary		1 sampling event	Megafauna	KOCH and WOLFF, 2002
Pernambuco, Northeast Brazil	PE	Mangrove	Itamaracá Island	Intertidal	Not determined	Megafauna	COELHO DOS SANTOS and COELHO, 2001
	PE	Tidal flat	Itamaracá Island	Intertidal (control area)	up to 153 days (experimental)	Macrofauna	BOTTER-CARVALHO et al., 2011
	PE	Mangrove	Suape Bay		1 sampling event	Megafauna	FARRAPEIRA et al., 2009
	PE	Channel	Fourteen estuaries of PE State	Subtidal	1 sampling event	Macrofauna	VALENÇA and SANTOS, 2012
Bahia, Northeast Brazil	BA	Mangrove and Channel	Cachoeira river, Ilhéus	Intertidal and subtidal	5 years - qualitative only	Megafauna	ALMEIDA et al., 2006
	BA	Channel	Paraguaçu river		6 months, 2 sampling events	Macrofauna	BARROS et al., 2008
	BA	Channel	Paraguaçu, Subaé and Jaguaripe rivers		6 months, 2 sampling events	Macrofauna	MAGALHAES and BARROS, 2011
	BA	Channel	Camamu Bay	Subtidal	1 sampling event	Macrofauna	PAIXÃO et al., 2011
	BA	Channel	Cachoeira river, Ilhéus	Subtidal	1 year, monthly	Macrofauna	OURIVES et al., 2011
	BA	Channel	Paraguaçu, Subaé and Jaguaripe rivers		6 months, 2 sampling events	Macrofauna	BARROS et al., 2012
Espírito Santo, Southeast Brazil	ES	Channel	Vitoria Bay	Intertidal and subtidal	1 year, every 3 months	Macrofauna	NALESSO et al., 2005
	ES	Rocky	Vitória Bay		3 months, 6 sampling events	Megafauna and macrofauna	ZALMON et al., 2011
Rio de Janeiro. Southeast Brazil	RJ	Mangrove	Sepetiba Bay	Intertidal	1 year, 6 sampling events	Megafauna	OSHIRO et al., 1998
	RJ	Channel	Guanabara Bay	Subtidal	3 years, 4 sampling events	Megafauna	LAVRADO et al., 2000
	RJ	Channel	Guanabara Bay	Subtidal	1 year, 2 sampling events	Macrofauna	SOARES-GOMES et al., 2012

Continued Table 1.

	RJ	Channel	Guanabara Bay	Subtidal	1 year, 2 sampling events	Macrofauna	SANTI and TAVARES, 2009
	RJ	Tidal flats	Guanabara Bay	Intertidal	1 year, 3 sampling events	Macrofauna	OMENA et al., 2012
	RJ	Rocky	Guanabara Bay	Intertidal	2 years, 8 sampling events	Megafauna	JUNQUEIRA et al., 2000
	RJ	Channel	Saquarema-Jaconé	Subtidal	1 year, 4 sampling events	Macrofauna	MENDES and SOARES-GOMES, 2011
São Paulo, Southeast Brazil	SP	Mangrove	Seven mangrove areas in the state	Intertidal	1 year, monthly	Megafauna	COLPO et al., 2011
	SP	Saltmarsh	Cananéia estuary	Intertidal	1 year, monthly	Macrofauna	TARARAM and WAKABARA, 1987
	SP	Channel	Cananéia estuary	Subtidal	1 sampling event	Macrofauna	TOMMASI, 1970
	SP	Tidal flats	Cananéia estuary	Intertidal	1 year, 5 sampling events	Macrofauna	VAROLI, 1990
	SP	Tidal flats	Santos estuarine system	Intertidal	1 year, 4 sampling events	Macrofauna	CORBISIER, 1991
	SP	Saltmarsh	Cananéia estuary	Intertidal	1 year, 8 sampling events	Macrofauna	ATTOLINI et al., 1997
Paraná, South Brazil	PR	Tidal flats	Guaratuba Bay	Intertidal	1 year, monthly	Megafauna	MASUNARI, 2006
	PR	Channel	Paranaguá Bay	Subtidal	1 sampling event	Macrofauna	LANA, 1986
	PR	Saltmarsh (*Spartina alterniflora*)	Paranaguá Bay	Intertidal	14 months, monthly sampling	Macrofauna	LANA and GUISS, 1991
	PR	Tidal flats	Paranaguá Bay	Intertidal	up to 18 days (experimental)	Macrofauna	NETTO and LANA, 1994
	PR	Tidal flats	Paranaguá Bay	Intertidal	6 months, 2 sampling events	Macrofauna	NETTO and LANA, 1997
	PR	Tidal flats, Salt marshes and Mangrove	Paranaguá Bay	Intertidal	1 sampling event	Macrofauna	LANA et al., 1997
	PR	*Spartina salt* marsh	Paranaguá Bay	Intertidal	6 months, 2 sampling events	Macrofauna	NETTO and LANA, 1999
	PR	Tidal flats and Channel	Baía de Guaratuba	Subtidal	1 sampling event	Macrofauna	BLANKENSTEYN and MOURA, 2002
	PR	Tidal flats	Paranaguá Bay	Intertidal	64 days (exeprimental)	Macrofauna	FARACO and LANA, 2003

Continued Table 1.

	PR	Tidal flats	Paranaguá Bay	Intertidal	95 days (experimental)	Macrofauna	FARACO and LANA, 2004
	PR	Salt marshes	Paranaguá Bay	Intertidal	120 days (experimental)	Macrofauna	PAGLIOSA and LANA, 2005
Santa Catatrina, South Brazil	SC	Mangrove	Estuary of Ratones River	Intertidal	1 sampling event	Meiofauna and Macrofauna	NETTO and GALLUCCI, 2003
	SC	Channel	Laguna Estuarine System	Subtidal	2 sampling events	Macrofauna	FONSECA and NETTO, 2006
	SC	Mangrove and Channel	Bay of Santa Catarina island	Subtidal	1 sampling event	Macrofauna	PAGLIOSA and BARBOSA, 2006
	SC	Channel	Laguna Estuarine System	Subtidal	1 year, 12 sampling events	Macrofauna	MEURER and NETTO, 2007
	SC	Mangrove	Santa Catarina island	Intertidal	1 year, 13 sampling events	Megafauna	BRANCO, 1990
Rio Grande do Sul, South Brazil	RS	Tidal flats	Patos Lagoon	Intertidal	1 sampling event	Macrofauna	ROSA and BEMVENUTI, 2004
	RS	Tidal flats	Patos Lagoon	Intertidal	6 months, 4 sampling events	Macrofauna	BEMVENUTI et al., 2003
	RS	Channel	Patos Lagoon	Subtidal	63 days (experimental)	Macrofauna	SOARES et al., 2004
	RS	Channel	Patos Lagoon	Subtidal	1 year, 4 sampling events	Macrofauna	BEMVENUTI et al., 2005
	RS	Tidal flats	Patos Lagoon	Intertidal	1 year, 12 sampling events	Macrofauna	COLLING et al., 2007
	RS	Saltmarsh (*Ruppia maritima*)	Patos Lagoon	Subtidal	2 sampling events	Macrofauna	ROSA and BE-MVENUTI, 2007

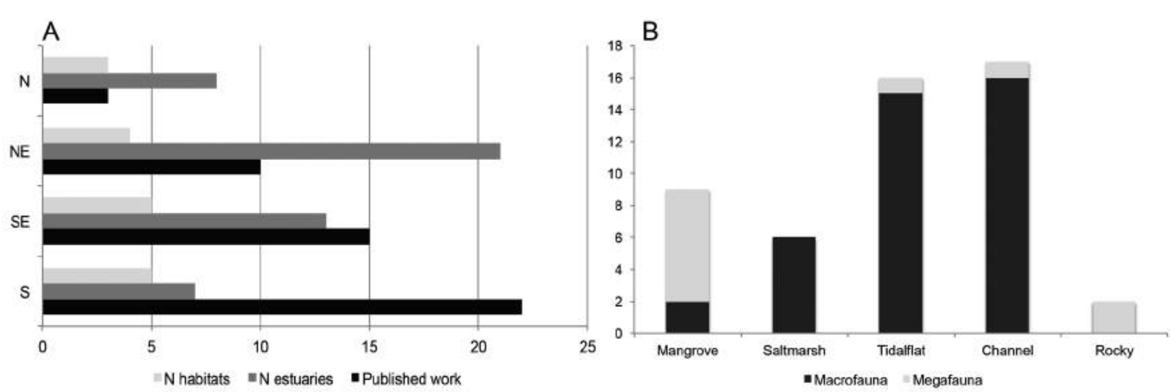

Figure 1. A. Distribution of selected published studies on benthic estuarine communities, number of estuaries and habitats within each region along the Brazilian coast from 1986 to 2012. B. Number of studies per habitat and proportion of studies addressing macrofaunal or megafaunal communities.

distribution and structure, or their relationship with environmental drivers and pollution effects. Descriptive studies overwhelmingly dominate those of all estuarine habitats and account for 60% of all published papers. Changes in community structure occur due to spatial changes of salinity, sediment composition and hydrodynamics at both tropical and subtropical estuaries (LANA et al., 1997; FONSECA and NETTO, 2006; COLLING et al., 2007; BARROS et al., 2008). The influence of habitat on benthic communities is also closely related to the vegetation and its organic detritus in addition to changes in the structure and distribution of communities between rainy and dry seasons (NETTO and LANA, 1999; PAGLIOSA and LANA, 2000; COLLING et al., 2007; MEURER and NETTO, 2007). Overall, there is a local increase in benthic species richness at vegetated sediments, most likely due the increased habitat complexity (NETTO and LANA, 1999).

The spatial and temporal patterns of benthic communities were investigated through a few (n = 1 to 4) sampling events during 6-month periods. The abiotic factors investigated included salinity, sediment properties (i.e. grain size and organic matter), presence or absence of vegetation and natural or anthropogenic disturbance (i.e. physical disturbance of sediment and pollution. Table 1). Seasonal dynamics of benthic fauna, over up to a year, were less often investigated (38% of published papers). Unvegetated flats and channels were commonly studied through monthly sampling (sometimes less frequently) for periods of a year. The benthic fauna of vegetated mangrove forests and salt marsh sediments were rarely sampled for periods longer than 6 months (Table 1). Long-term studies, which includes those on inter-annual temporal scales of > 2 years, are clearly missing for all benthic estuarine habitats except for a few exceptions across Brazil (n = 4). Information on seasonal and interannual variability of benthic estuarine communities is spatially highly limited. For example, we have found a 4-year qualitative survey on the carcinofauna of mangrove forests and estuarine sediments in NE Brazil (ALMEIDA et al., 2006). Another 3-year sampling with only 4 trawling campaigns studied the benthic megafauna within Guanabara Bay, which was also studied in respect to its rocky shore communities over a 2-year period (JUNQUEIRA et al., 2000; LAVRADO et al., 2000). The longest time series study of benthic macrofauna was carried out on a saltmarsh in Paranaguá Bay (LANA and GUISS, 1991), which was sampled monthly for 14 months.

DISCUSSION

Moving from community structure to ecological processes

There is an urgent need to increase the number of field surveys in poorly studied regions. Past and current descriptive efforts are clearly important to describe and discriminate varying estuarine patterns along the Brazilian coast. As these estuaries are fundamentally distinct in respect to their geomorphology and oceanographic conditions and are under various climatic regimes, additional investigations will certainly lead to a better recognition of associated benthic communities and site-specific responses (GILLANDERS and KINGSFORD, 2002; SOARES et al., 2014). Indeed, there is strong evidence for local and regional heterogeneity of estuarine benthic communities among habitats (NETTO and LANA, 1997; EDGAR and BARRETT, 2002; BARROS et al., 2012). Such heterogeneity may lead to variable community-environment responses of benthic fauna at different estuaries. In any case, these surveys would clearly benefit from standard protocols for community assessment and data analysis, allowing the identification of large scale patterns and potentially leading to more accurate models.

However, it is also necessary to move research questions from the basic descriptions of community structure to the understanding of the ecological processes that regulate benthic dynamics in Brazilian estuaries. The investigation of ecological processes in benthic communities has advanced through intensive sampling and field manipulative experiments in SE and S Brazil, with greater effort directed to unvegetated flats and saltmarshes. As has been revealed for temperate and tropical estuaries in the Northern hemisphere, significant differences in community structure, succession and trophic processes occur between vegetated and unvegetated sediments in subtropical estuaries (LANA and GUISS, 1992; NETTO and LANA, 1999). Manipulative and mensurative experiments also revealed the responses of benthic communities to nutrient loading and pollution effects, which greatly improved our understanding of mechanisms of community resilience and succession after disturbance (FARACO and LANA, 2003; MENDES and SOARES-GOMES, 2011; GERN and LANA, 2013; SOUZA et al., 2013). Recognising these patterns on local and regional scales allows for better predictive models of benthic community responses to habitat modification, species invasion and subsequent changes in sediment biogeochemistry (NEIRA et al., 2005; DEMOPOULOS et al., 2007; CANNICCI et al., 2008; DEMOPOULOS and SMITH, 2010; SWEETMAN et al., 2010). In order to build strong models to detect wide ecosystem impacts from climate change (SCAVIA et al., 2002; KOTTA et al., 2009; SEMENIUK, 2013), we will need replicated experiments on a large latitudinal scale at several Brazilian estuaries.

Broad changes in the structure and functioning of benthic estuarine communities are expected with the projected changes in sea level, temperature and rainfall (NAJJAR et al., 2000; GILLANDERS and KINGSFORD, 2002; MILLIMAN et al., 2008; NICHOLLS and CAZENAVE, 2010; DONEY et al., 2012; BERNARDINO et al., 2015a). Significant changes in rainfall extremes and dry cells have been projected for South America (MARENGO et al., 2010). They include an increase in extreme precipitation events over most of Southeastern South America and Western Amazonia consistent with projected increasing trends in total rainfall. Smaller or no changes in rainfall intensity have been foreseen for Northeast Brazil and Eastern Amazonia, though significant changes are expected in the frequency of consecutive dry days. On estuary- scale, benthic species distribution, diversity and dynamics across salinity gradients may change significantly (ELLIOTT and WHITFIELD, 2011; WHITFIELD et al., 2012). As salinity-community patterns for Brazilian estuaries are understudied in most regions, the loss of species or community changes in these areas will lead to uncertainties about changes in key ecological processes. The benthic fauna associated with vegetated habitats will also be heavily impacted due to habitat loss, which will impact production and trophic processes (LEE, 1998). Sea-level rise effects on Brazilian estuaries are largely uncertain, but will likely lead to loss of mangrove and saltmarsh ecosystems and their services, including carbon sequestration (DUARTE et al., 2005; DONATO et al., 2011). It is clear that most estuarine areas within urban regions will be severely impacted or disappear as vegetated ecosystems will fail to migrate onshore due to coastal development (SHORT and NECKLES, 1999; ALONGI, 2008).

In summary, few ecological and biogeochemical processes mediated by benthic organisms in Brazilian estuaries have been investigated, which precludes reasonable mitigation and conservation strategies if projected changes are confirmed. Mechanisms of benthic production and functional effects on communities in response to natural and anthropogenic disturbance need to be investigated on a multi-scale perspective. It is clear that current and future investigations of estuarine processes need to include the role of benthic communities in sediment biogeochemistry, to address the ecological effects of changes in environment and habitat, and finally to make quantitative predictions of potential environmental, economical and societal changes.

Increase long-term scientific and monitoring efforts

The question of scale in ecology has received much recent attention (LEVIN, 1992; SCHNEIDER, 2001). Studying large temporal scales of ecological processes has been a major challenge for ecologists as well as securing funds for the long-term approaches that are needed to understand these processes. In this context, studies of pattern have become still been more frequent in science, but are strikingly few regarding estuarine ecosystems in Brazil. A number of the ecological benefits provided by estuaries have been independently investigated at a number of sites in Brazil over recent decades (RONDINELLI and BARROS, 2010; PENDLETON et al., 2012; VILAR et al., 2013), but we have no systematic efforts, dedicated funding programs or networks to study Brazilian estuaries. Additionally, the short-term scale (i.e. less than 1-yr) of most studies means that we do not have scientific data on relevant temporal scales to characterize, manage or protect most estuaries and their associated communities in Brazil.

As estuaries are naturally dynamic ecosystems and associated with coastal and riverine hydromorphology, we need to understand changes in their communities and ecological processes on decadal scales in the light of meaningful temporal scales of riverine, marine and climate forces (SCAVIA et al., 2002; ELLIOTT and WHITFIELD, 2011). Long-term studies, with duration of > 2yrs, have an increased power to detect community-wide responses to intra-annual and inter-annual changes in estuarine dynamics. A number of community processes driven by benthic organisms suffer significant changes on time scales longer than a year. For example, population dynamics and benthic annual production rates may vary significantly on annual and decadal scales due to changes in estuarine productivity, temperature, disturbance regimes, catastrophic events and interacting factors (KOTTA et al., 2009; DOLBETH et al., 2011). Although functional indices such as productivity regimes offer advantages in depicting ecosystem-wide responses, large variability in productivity may occur between estuaries due to site-specific differences such as pelagic productivity (CONDIE et al., 2012). Therefore, the multiple mechanisms that lead to changes in production and population dynamics over long-term periods suggest that estuarine ecosystems must be investigated on multiple scales.

The ReBentos Estuaries working group has proposed a study protocol for benthic estuarine communities that meets the above criteria of i) standardisation of methods; ii) working with functional and biodiversity indices, and iii) multiple scales. The protocol has been designed to address projected and observed changes in mean atmospheric temperatures and in yearly rainfall at estuaries in the major climatic regions of Brazil (MARENGO et al., 2010; BERNARDINO et al., 2015b). With scientific hypotheses based on projected changes, we suggested a standard protocol for studying temporal patterns in productivity and diversity of megafaunal and macrofaunal benthic communities. The working group has so far started field work on a total of eight estuaries located in the major regions of Brazil. These estuaries were selected based on their accessibity to various research groups and on existing protected areas (i.e. federal, state or municipal). At each estuary, the working group has started quarterly acquisition of biological and environmental data, with replicated campaigns after dry and wet seasons. We believe that these assessments must be continued, not only to reveal large scale spatial and temporal patterns of benthic estuarine communities, but also to test the hypothesis with long-term data. However, although the ReBentos working group has received a limited startup funding of 3 years, continuous assessments at these estuaries from Northern to Southern Brazil may have to be interrupted.

What international programs can teach us

The International Long-term Ecological Research Network (ILTER) is an example of a global network of scientists engaged in long-term, site based ecological and socioeconomic research, with the mission of understanding global ecosystems and providing potential solutions to current and future global problems, considering the human dimensions of environmental change. The goals of ILTER are to coordinate long-term ecological research in integrated and collaborative networks; to improve comparability of long-term ecological data through simple field and lab protocols; to generate and transmit better scientific information to scientists, policymakers and the public; and to facilitate education of the next generation of long-term scientists. The PELD program (Long-term Ecological Researches), created by the Brazilian National Research Council (CNPq) - Ministry of Science, Technology and Innovation in 1998, was clearly influenced by ILTER. The PELD program is promoting and funding a series of fruitful projects, but none of them have addressed estuarine benthic dynamics on a national scale (TABARELLI et al., 2013).

The U.S. National Environmental Protection Agency has started an Estuary Program (NEP) that initiated several networks with broad objectives including protection and resource governance (SCHNEIDER et al., 2003). Providing up to 5-year funding for creation of management plans for 28 estuaries across the U.S., the NEP program has fostered networks with regional representatives of government, business, citizens, educators and researchers. These networks have been successfully bridging scientific knowledge with policy discussions, and have resulted in the better assessment of impacts on estuaries and their watersheds (SCHNEIDER et al., 2003; MERRIFIELD et al., 2011). Although NEP programs often target regional human impacts on estuaries, the identification of commonalities or dissimilarities in estuarine ecosystems significantly ensures better climate change response and management in these areas (MERRIFIELD et al., 2011). Cimate preparedness and response for estuaries also comes from the US EPA agency specific program named Climate Ready Estuaries (http://water.epa.gov/type/oceb/cre/index.cfm). This program assists the NEP program directly through network actions, and both programs benefit from information produced on scales from local to regional. These joint network efforts are excellent innitiatives for the better practice of estuarine management.

In the European Union, environmental threats to coastal areas have led to political action to protect estuarine and other ecosystems from the effects of human activities (FERREIRA et al., 2011). These policies ultimately led to a Water Strategy Framework Directive (WFD) designed to investigate ecosystem function and to establish guidelines for assessing environmental quality and long-term monitoring of coasts, estuaries and their watersheds (PARLIAMENT, 2000). The WFD has resulted in a number of studies that have developed guidelines to assess all aspects of water and ecosystem quality. As every EU country has been required to follow those directives, national scientific networks across the EU have applied integrated studies regionally to evaluate the ecosystem health of estuaries and their watersheds. In the estuaries and on the coasts of Europe, specific tools for the assessment of ecological status using benthic communities have been created (BORJA et al., 2000) and these have been independently tested in Brazil (MUNIZ et al., 2005; VALENÇA and SANTOS, 2012).

Many other international initiatives across Europe have tested and developed guidelines to investigate benthic estuarine habitats in the long-term with management purposes (QUINTINO et al., 2006; RODRIGUES et al., 2011). As a result, a regulatory directive from the EU Parliament encouraged the creation of scientific and political networks with a view to the assessment of regional ecosystems, the testing of scientific methods and protocols, and coastal management.

These integrated efforts undoubtedly demonstrate that successful programs to protect estuaries call for sound science allied to political and societal engagement. The ReBentos network has started a unique and fruitful network - mainly composed of scientists - that could arouse interest in estuarine management and protection. However, Brazilian efforts to protect estuaries, and most coastal ecosystems, will be largely ineffective if only scientists pursue these objectives (SUNDERLAND et al., 2009). Successful programs to protect Brazilian estuaries from human and climate change impacts will need to be funded by public and private agencies (municipal, state and federal), with the involvement of all stakeholders including scientists, interested parties (e.g. traditional fishermen and industry), private and non-governmental organizations; and result in specific products for management of estuarine ecosystems. Funding for these programs needs to be priorized by federal and state environmental agencies (e.g. CNPq, CAPES, IBAMA; the Ministry of the Environment, the Ministry of Science) which are clearly key players responsible for ecosystem use and conservation. These programs must result in sound scientific practices, with well organized and public data bases (i.e. also funded and maintained by those sources). These programs should be further accompanied and evaluated by progress reports and subjected to rigorous national and international panel evaluations.

Prospects of the studies of the estuaries selected by the ReBentos network

Estuarine benthic communities have been extensively studied across the world and these studies include long-term network initiatives for monitoring. The overall result of changes in species richness, density and biomass related to salinity (MORTIMER et al., 1999; JOSEFSON & HANSEN, 2004), sediment composition (MORRISEY et al., 2003), nutrient input (EDGAR & BARRETT 2002), geomorphology (HIRST, 2004) and oxygen availability (ROSENBERG, 1977; NILSSON & ROSENBERG, 1997) is generally the same. Changes in these abiotic parameters are also related to river and ocean dynamics, natural seasonal climatic changes or anthropogenic impacts, influencing benthic communities (MONTAGNA & KALKE, 1992; FUJII, 2007). Nevertheless, South American estuaries are frequently not included in the search for general ecological models (BARROS et al., 2012), and understanding the patterns and processes which occur along the Brazilian coast would constitute an important contribution to global discussion, due to the extent and diversity of the Brazilian coastline.

The macroscale investigation started by the ReBentos network was the first step towards an integrated approach which takes into account the variety of Brazilian estuaries, their benthic biodiversity and the assessment of the effects of projected climatic change on the goods and services they provide. The effects of large-scale factors on populations and communities are usually underpinned by hierarchical (top-down scale mediated processes) or multiscale (interactions among scales mediated processes) perspectives (HEWITT and THRUSH, 2007; 2009). Both perspectives must take spatial and temporal variation into account. Moving forward, registering, understanding, and reviewing climate change effects on estuarine benthos will require continuous and long-term monitoring. The systematic application of established monitoring protocols will highlight the large-scale and long-term relative importance of environmental factors in influencing spatial and temporal dynamics of benthic richness and abundance, and how their loss can affect estuarine resources and services. The integrated management across spatial and temporal scales and frequent monitoring of estuarine patterns and processes are essential tools for coastal management, since regions under higher pressure from human activities are more suceptible to climatic change impacts. Based on knowledge of the patterns and processes involved in estuarine systems on the long term, further conservation and management decisions can be taken to mitigate impacts. Thus our ability to make better predictions and to provide resource management agencies and policymakers with the best scientific information will depend largely on an increased effort aimed at using integrated research networks over long-term scales.

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ReBentos

Brazilian coral reefs in a period of global change: A synthesis

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Abstract

Brazilian coral reefs form structures significantly different from the well-known reef models, as follows: (i) they have a growth form of mushroom-shaped coral pinnacles called "chapeirões", (ii) they are built by a low diversity coral fauna rich in endemic species, most of them relic forms dating back to the Tertiary, and (iii) the nearshore bank reefs are surrounded by siliciclastic sediments. The reefs are distributed in the following four major sectors along the Brazilian coast: the northern, the northeastern and the eastern regions, and the oceanic islands, but certain isolated coral species can be found in warmer waters in embayments of the southern region. There are different types of bank reefs, fringing reefs, isolated "chapeirões" and an atoll present along the Brazilian coast. Corals, milleporids and coralline algae build the rigid frame of the reefs. The areas in which the major coral reefs occur correspond to regions in which nearby urban centers are experiencing accelerated growth, and tourism development is rapidly increasing. The major human effects on the reef ecosystem are mostly associated with the increased sedimentation due to the removal of the Atlantic rainforest and the discharge of industrial and urban effluents. The effects of the warming of oceanic waters that had previously affected several reef areas with high intensity coral bleaching had not shown, by the time of the 2010 event, any episodes of mass coral mortality on Brazilian reefs.

Descriptors: Coral reefs, Global changes, Coral bleaching, Endemic fauna.

Resumo

Os recifes de coral do Brasil formam estruturas significativamente diferentes dos modelos conhecidos: (i) possuem uma forma de crescimento de pináculos coralíneos em forma de cogumelo, chamados "chapeirões", (ii) são construídos por uma fauna coralínea com baixa diversidade e rica em espécies endêmicas, sendo grande parte destas formas relíquias do período Terciário e (iii) os recifes costeiros estão num ambiente dominado por sedimentos siliciclásticos. Os recifes estão distribuídos em quatro áreas ao longo da costa brasileira: regiões norte, nordeste, leste, e nas ilhas oceânicas, mas espécies isoladas de coral podem ser encontradas em águas mais quentes nas enseadas da região sul. Diferentes tipos de banco recifais, recifes em franja, "chapeirões" isolados e um atol estão presentes ao longo da costa brasileira. Corais, milleporídeos e algas coralinas incrustantes constroem a estrutura rígida dos recifes. As áreas em que ocorrem os maiores recifes de coral correspondem às regiões nas proximidades de centros urbanos que estão experimentando crescimento acelerado e rápido desenvolvimento do turismo. Os principais efeitos antropogênicos sobre o ecossistema recifal estão associados, essencialmente ao aumento da sedimentação devido à remoção da mata atlântica e as descargas de efluentes industriais e urbanos. Os efeitos do aquecimento das águas oceânicas que vem afetando várias áreas de recifes, com alta intensidade de branqueamento de coral, não causaram mortalidade em massa nos recifes brasileiros até o evento de 2010.

Descritores: Recifes de corais, Mudanças globais, Branqueamento de coral, Fauna endêmica.

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INTRODUCTION

The reef ecosystem has been rated among the most complex and valuable of all of the marine coastal systems on Earth - along with the mangrove forests - because of the varied goods and services that they supply to the adjacent coastal populations and their regional and global contributions. Among those important contributions are subsistence fishing and extraction, the tourism and recreational industries, shoreline protection and research/educational activities, and certain useful pharmaceutical products (SPURGEON, 1992; CARTÉ, 1996; CONSTANZA et al., 1997; BIRKELAND, 1997; MOBERG; FOLK, 1999; CESAR; VAN BEUKERING, 2004). Coral reefs occupy approximately 0.02% of the ocean area (SPALDING; GRENFELL, 1997), and harbor approximately ¼ of all of marine species (DAVIDSON, 1998). For centuries, populations from many tropical islands worldwide and from certain Brazilian coastal areas have depended on the coral reef resources for their sustenance and livelihoods. (SALVAT, 1992; MOBERG; RÖNNBÄCK, 2003; FERREIRA et al., 2006).

However, coral reefs are one of the ecosystems in the world most sensitive to global warming. Coral reefs are among the Earth's ecosystems most severely threatened by rising sea temperatures. Nearly all of the reefs have been heated above their maximum temperature threshold; many have already lost a significant portion of their corals, and approximately 30% to 40% of the world's coral reefs are already severely degraded (GLYNN, 1993; BROWN, 1997; WILKINSON, 2000, 2002, 2004, 2008; HUGHES et al., 2003; DONNER et al., 2005; PANDOLFI et al., 2005; HOEGH-GULDBERG, 1999; HOEGH-GULDBERG et al., 2007; WILKINSON; SOUTER, 2008; EAKIN et al., 2010; OXENFORD et al., 2010; BURT et al., 2011; DE'ATH et al., 2012; GUEST et al., 2012).

This study presents a synthesis of the Brazilian coral reefs, their major reef types, their distribution along the tropical coast, the diversity of the reef building coral fauna, the developmental history of the reefs and the major threats affecting reef diversity. Emphasis is placed on the effects of ocean warming on Brazilian coral reefs, and we contribute methods for the evaluation and mitigation of these effects.

RESULTS AND DISCUSSION

Major coral reef types and their distribution

Brazilian coral reefs are one of the most prominent marine ecosystems, comprising the largest and the richest area of reefs in the entire southwestern Atlantic Ocean. These reefs are spread over 3,000 km along the Brazilian coast, from 0º50'S to 18º00'S, and they can be generally divided into the following four main reef regions: the northern region, the reefs of the northeastern coast, the reefs of the eastern coast and the reef ecosystems of the oceanic islands (LEÃO et al., 2003; FERREIRA et al., 2013); however, certain coral species are also found on the southeastern and southern coasts of Brazil (CASTRO et al., 1995; MIGOTTO et al., 1999; OIGMAN-PSZCZOL; CREED, 2004, 2006) (Figure 1). These reefs are composed of shallow bank reefs attached to the coast, fringing reefs bordering island shores, coral knolls, patch reefs, isolated bank reefs of different forms and sizes off the coast, and coral pinnacles known as the Brazilian "chapeirões" (LEÃO et al., 2003; FERREIRA et al., 2006; RODRIGUEZ-RAMIREZ et al., 2008; KIKUCHI et al., 2010).

In the northern region (from 0º50'S to 5º00'S), the most well-known reefs are those of the Parcel de Manuel Luiz on the shelf of the state of Maranhão approximately 90 km off its coastline. These reefs grow as giant pinnacles to depths of approximately 25 to 30 m, and their tops reach up to 2 m of water depth, but during the spring low tides, some are at sea level (COURA, 1994; AMARAL et al., 2006, 2007; MAIDA; FERREIRA, 1997). Eastward from this area as far as São Roque cape, certain patch and bank reefs on the inner shelf have been mapped along the coast of the state of Ceará and the northern part of the coast of Rio Grande do Norte state (LABOREL, 1969, 1970; SANTOS et al., 2007).

The northeastern region (from approximately 5ºS to 10ºS) is composed of the coastal reefs extending from the cape São Roque to the São Francisco river mouth, off the states of Rio Grande do Norte, Paraíba, Pernambuco and Alagoas. Coral reefs abound on the inner shelf. These coral reefs are mostly patch or elongated banks reefs; some are attached to the coast and others are several kilometers offshore, generally lying parallel to the coast at depths of approximately 5 m to 10 m. Although not yet cored, the spatial arrangement and elongation of these reefs suggest that most of them may have grown over lines of beach rock (LABOREL, 1969; DOMINGUEZ et al., 1990; TESTA, 1997; MAIDA; FERREIRA 2003; COSTA et al. 2005; FERREIRA et al. 2006; CORREIA; SOVIERZOSKI, 2010; CORREIA, 2011) (Figures 2 and 3).

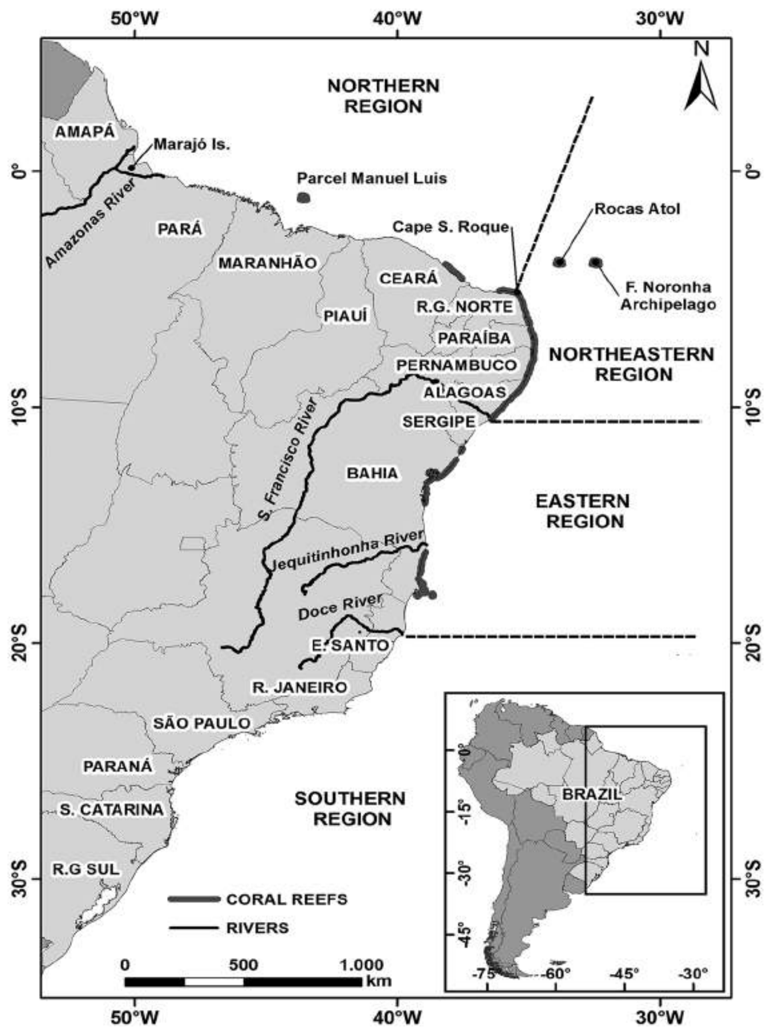

Figure 1. Location of the coral reef regions along the Brazilian coast.

Figure 2. Aerial photograph of Porto de Galinhas coral reef on the coast of the State of Pernambuco, on the northeastern coast of Brazil.

Figure 3. Aerial photograph of the Ponta Verde reef attached to the coast of the State of Alagoas on the northeastern coast of Brazil.

The eastern region (from approximately 10ºS to 18ºS) extends between the São Francisco and the Doce Rivers over 1,000 km along the coasts of the states of Sergipe and Bahia. This is the largest coral reef area along the entire Brazilian coast. The Sergipe shelf had been considered to lack coral reefs until recently when submerged reef structures that have not yet been mapped, were found (NEVES et al., 2005, 2006, 2010). Along the coast of the state of Bahia, the reefs can be subdivided into the following four major reef areas: the North Bahia coast, the Todos os Santos and Camamu Bays, the Cabrália/Porto Seguro area and the Abrolhos Bank reef complex. The North Bahia reefs are composed of shallow isolated bank reefs of various sizes that occur between the beaches of Abaí and Praia do Forte (KIKUCHI; LEÃO, 1998, KELMO; ATTRILL, 2001, LEÃO et al., 2003) (Figures 4 and 5). A cored reef revealed Holocene carbonate buildups with a thickness of approximately 10 m lying on a pre-Cambrian rocky substrate (NOLASCO; LEÃO, 1986), and deeper reef structures occur towards the continental shelf break (KIKUCHI; LEÃO, 1998). In the area from Todos os Santos Bay to Camamu Bay, relatively continuous shallow fringing reefs border the islands' shores, and shallow bank reefs having a relatively round profile are to be observed in the interior of the bays (LEÃO et al., 2003; CRUZ et al., 2009, 2015; KIKUCHI et al., 2010). The Pinaunas reef that borders the shore of Itaparica Island in Todos os Santos Bay has a cored reef structure that is 8 m thick and of Holocene age that grew above the island substrate (ARAUJO et al., 1984) (Figure 6), and near Camamu Bay, a non-continuous line of shallow reefs borders the shore of the Tinharé and Boipeba Islands (Figure 7).

Figure 4. Aerial photograph of the Praia do Forte reef along the coast of the State of Bahia, in Eastern Brazil.

Figure 5. Aerial photograph of a reef attached to the coast of Itacimirim Beach on the coast of the State of Bahia, in Eastern Brazil.

Figure 6. Aerial photograph of the Pinaunas fringing reef bordering the Itaparica Island shore at the entrance of Todos os Santos Bay, in Eastern Brazil.

Figure 7. Aerial photograph of the shallow fringing reefs of Tinharé Island on the eastern coast of Brazil.

The area of Cabralia/Porto-Seguro is characterized by the presence of bank reefs of various shapes and dimensions in water no deeper than 20 m, running mostly parallel to the coastline (COSTA JR et al., 2006) (Figure 8). The elongated reefs may have grown on submerged strings of beach rocks (LABOREL, 1970). A few kilometers off the coast of Porto-Seguro, the Recife de Fora lies the reef habitat most visited by tourists in this entire region. Southward, there are the Itacolomis reefs, which are the beginning of the occurrence of the Brazilian giant "chapeirões" and isolated bank reefs separated from one another by deep irregular channels (CASTRO et al., 2006a; CRUZ et al., 2008).

Figure 8. Aerial photograph of reefs of the Cabrália and Porto-Seguro region on the eastern coast of Brazil.

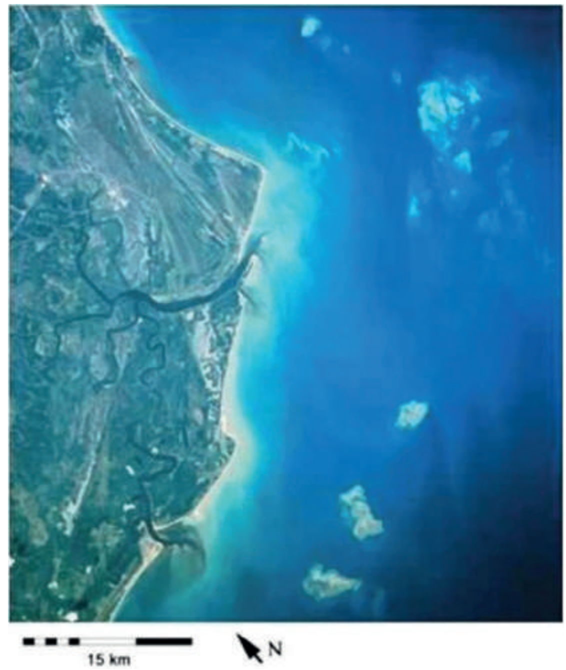

Figure 9. Satellite image illustrating the coral reefs of the coastal arc of Abrolhos.

Figure 10. Aerial photograph of shallow fringing reefs surrounding the islands of the Abrolhos Archipelago in the southern portion of the state of Bahia, in Eastern Brazil.

At approximately 17ºS, the continental shelf widens to form the Abrolhos Bank on which the richest and best known coral reefs of the eastern Brazilian region are located (HARTT, 1870; LABOREL, 1970, LEÃO, 1983; LEÃO et al. 1988, LEÃO et al., 1996, 1999; LEÃO; GINSBURG, 1997; VILLAÇA; PITOMBO, 1997; PITOMBO et al., 1988; LEÃO; KIKUCHI, 2001; LEÃO et al., 2003, 2006; PRATES, 2006; LEÃO; FOURNIER, 2007; LEÃO et al., 2008; FRANCINI-FILHO et al., 2008, 2010; among others). These reefs form the following two arcs: the coastal arc composed of bank reefs of various shapes and dimensions and the outer arc eastward of the islands of the Abrolhos Archipelago, which is formed by isolated "chapeirões" in water deeper than 20 m. Incipient fringing reefs border the shores of the five islands that compound the archipelago (Figures 9 and 10). A cored reef on the coastal arc revealed a Holocene coral reef structure, over 12 m thick, lying on a reefal carbonate rock of probable Pleistocene age (LEÃO; LIMA, 1982; LEÃO; KIKUCHI, 1999). Southward in the Abrolhos Bank, in the northern part of the coast of Espírito Santo state, several coral species have been described (AMARAL et al., 2007).

Mesophotic reefs have been described across the mid and outer shelves of the Abrolhos Bank, at depths from 25 to 90 m. These reefs are structures described as submerged pinnacles, coalescent reefs 2-3 m high with sinkhole-like depressions known as "buracas". These reef structures are almost drowned reefs with low coral coverage. In the deep pinnacles, the coral *Montastraea cavernosa* dominates, and a sparse occurrence of *Siderastrea* spp., *Agaricia* spp., *Porites* spp., *Madracis* spp., *Favia* spp. and *Scolymia* spp., along with the black corals Cirripathes and Antipathes have been observed (MOURA et al., 2013; BASTOS et al., 2013).

In the southeastern and southern regions, from the mouth of the Doce River (19º 30'S) to the coast of the state of São Paulo, no reef is known, although corals have been found. At Arraial do Cabo in the state of

Rio de Janeiro, in the so-called "Laborel's coral oasis" (LABOREL, 1969), the coral species *Siderastrea stellata* and *Mussismilia hispida* have been found on several rocky shores (CASTRO et al., 1995; OIGMAN-PSZCZOL; CREED, 2004, 2006). The species *Mussismilia hispida* has also been observed on the coast of São Paulo state (MIGOTTO, 1995; MIGOTTO et al., 1999).

The reef ecosystems of the Oceanic Islands are composed of the coral communities of the Atol das Rocas, the islands of Fernando de Noronha and the São Pedro and São Paulo archipelago and certain coral species of the islands of Trindade and Martin Vaz. Rocas (03º51'S - 33º49'W) is an atoll that developed on the flat top of a seamount. Rocas has an elliptical shape with the longer axis (3.5 m long) oriented E-W and the minor axis (approximately 2.5 m long) oriented N-S. The reef ring is open on its western and northern sides. Despite its small dimensions, all of the characteristic features of a reef can be distinguished, such as the reef front, reef flat and a shallow lagoon. Rocas has been the subject of many studies over the last decades (MAŸAL; BEZERRA, 1995; KIKUCHI; LEÃO, 1997; ECHEVERRIA et al., 1997; MAIDA; FERREIRA, 1997; GHERARDI; BOSENCE, 1999, 2001; KIKUCHI, 2002; GHERARDI; BOSENCE, 2005; PEREIRA et al., 2010; SOARES et al., 2011a, 2011b) (Figure 11). The Fernando de Noronha Archipelago (03º51'S - 32º25'W) is composed of 21 islands and islets of volcanic origin, located approximately 350 km off the coast of Rio Grande do Norte state. These islands are part of the volcanic mountains of the Fernando de Noronha Chain (FERREIRA et al., 2013). True reefs have not been found on the islands, but an abundant coral fauna grows on their rocky shores (PIRES et al., 1992; MAIDA et al., 1995; MAIDA; FERREIRA, 1997; CASTRO; PIRES, 2001; PRATES, 2006; AMARAL et al., 2009; MILOSLAVICH et al., 2011). The São Pedro and São Paulo Archipelago (00º56'S - 29º22'W) consists of 15 rocky islets located approximately 1100 km off the coast of Rio Grande do Norte state, the largest being the Belmonte Islet, less than 100 m long and 50 m wide (VASKE JR et al., 2010). Few coral species have been reported on the rocky shores of these islets (LABOREL, 1970; AMARAL et al., 2000). The rocky islands of Trindade and Martin Vaz (20º30'S - 29º20'W) belong to the Vitória - Trindade Rock Chain, located approximately 1200 km off the coast of Espírito Santo state. No true reefs exist, but certain coral species have been reported on these islands (FLOETER et al., 2001).

Figure 11. Satellite image of Atol das Rocas.

The diversity of the reef building coral fauna

The Scleractinian corals are the major framework reef builders and provide most of the structural complexity in the reef ecosystem. These corals grow into a rock-like colony that forms the basic structure of the coral reefs (GUEST et al., 2012) because they have a symbiotic relationship with the micro algae zooxanthelae, which supply the coral polyps with sufficient energy to build their protective calcium carbonate skeleton.

The Scleractinia coral fauna of Brazil has the following three distinctive characteristics: i) it is a low diversity coral fauna (23 corals and five hydrocorals) compared with that of the North Atlantic reefs; ii) the major reef builders are species endemic to Brazilian waters, and iii) it is predominantly composed of massive forms.

The first descriptions of the Brazilian corals were taken from those collected during Hartt's expeditions to Brazil (HARTT, 1869, 1870) and subsequently identified by VERRILL (1868, 1901, 1912). Later, LABOREL (1967, 1969) compared Verrill's taxonomy with contemporary forms and Tertiary fossils and corroborated Verrill`s remarks that among the Brazilian reef frame builders, endemism is rather strong. Later in the 20th century, BELEM et al. (1986) and CASTRO (1994) confirmed and expanded Laborel's list, and, more recently, additions of new coral and hydrocoral species have been made. NEVES et al. (2005, 2006, 2008, 2010) have described two new occurrences of the genus *Siderastrea* in Brazil, *Siderastrea radians* and *S. siderea*, and a new species of *Scolymia*, *S. cubensis* (NEVES et al., 2006). AMARAL et al. (2007, 2008) have described the new species *Millepora laboreli,* from the reefs of the Manuel Luis State Park (Maranhão State).

Two invasive coral species have also been added to the list of the Brazilian coral fauna, *Tubastraea tagusensis* and *T. coccinea.* These invasive coral species have been described in reefs from Todos os Santos Bay (MIRANDA et al., 2012; SAMPAIO et al., 2012), on rocky shores in the state of Rio de Janeiro (PAULA; CREED, 2005; CREED, 2006; CREED; PAULA, 2007; FERREIRA et al., 2013), and incrusting oil platforms in the states of Santa Catarina (MANTELATTO et al., 2011, RIUL et al., 2013) and Espírito Santo (COSTA et al., 2014). To date, 23 species of stony corals and five species of hydrocorals constitute the cnidarian fauna of Brazil (Figure 12).

The major environmental effects on the reefs

Natural disturbances

Because the Brazilian reefs experience no hurricanes and overlie a passive continental shelf, the effects of the natural disturbances recorded in our reefs are related only to the sea level oscillations that have occurred over the last 5 ky and their effects.

The sea level history during the late Holocene period shows that the Brazilian coast experienced relatively considerable sea level fluctuations (MARTIN et al., 1979, 1985). These sea level oscillations have exerted profound effects on the evolution of the coral reefs. The late Holocene regression that occurred over the last 5 ky has been responsible for the degradation phase of the nearshore reefs. As previously described, the lowering of the sea level exposed the reef tops to marine erosion, dissolution and extensive bioerosion. Furthermore, the reef communities dwelling on these tops experienced stress, primarily resulting from strong solar radiation and high levels of sedimentation and water turbidity. Several 14C dates from the tops of the coastal bank reefs, ranging from 3.18 to 6.00 ky BP (LEÃO et al., 1985, 1997; MARTIN et al., 1996; KIKUCHI; LEÃO, 1998; LEÃO et al., 2003; LEÃO; KIKUCHI, 2005), provide evidence that the reefs reached heights higher than the present sea level and that they were truncated by erosion due to falls in sea level. On these flattened reef tops, which are completely subaerially exposed during low tides, living corals occur only within the tidal pools.

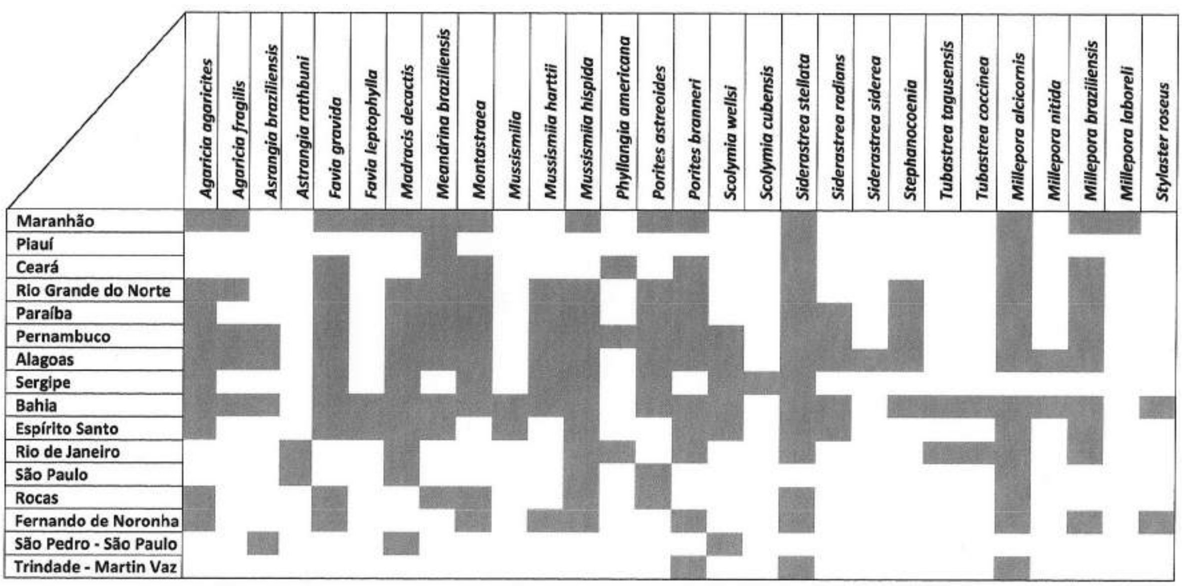

Figure 12. Distribution of coral and hydrocoral species along the coast of Brazil. Northern Region: states of Maranhão, Ceará, Piauí and north part of Rio Grande do Norte. Northeastern Region: east coast of Rio Grande do Norte, and the states of Paraíba, Pernambuco and Alagoas; Eastern Region: Sergipe, Bahia and Espírito Santo states; Southeastern and Southern Regions: Rio de Janeiro and São Paulo; Oceanic Islands: Rocas, Fernando de Noronha, São Pedro/São Paulo Archipelago and islands of Trindade and Martin Vaz. Data from: LABOREL (1969,1970); BELÉM et al. (1986); TESTA (1997); CASTRO (1994); CASTRO et al. (2006); MAŸAL; BEZERRA (1995); ECHEVERIA et al. (1997); MAIDA; FERREIRA (1997); AMARAL et al. (2006, 2007, 2008, 2009); PAULA; CREED (2005); OIGMAN-PSZCZOL; CREED (2004, 2006); CASTRO et al. (2006a); CREED (2006); NEVES et al. (2005, 2006, 2008, 2010); CREED; PAULA (2007); CREED et al. (2008); CORREIA; SOVIERZOSHI (2010); CORREIA (2011); MANTELATTO et al. (2011); MIRANDA et al. (2012); SAMPAIO et al. (2012).

In these tidal pools, variations in the water temperature and salinity along with long exposures to strong solar radiation are stress factors for most of the coral species. Small colonies of the endemic species *Siderastrea stellata* and *Favia gravida* are the only corals that inhabit this reef environment.

Increased coastal sedimentation during the regression subjected the reefs to the influence of a highly siliciclastic sediment influx. Data from several areas along the northeastern and eastern coasts of Brazil show that the nearshore reefs are located in a sedimentary province dominated by terrigenous sediments, either relict or modern. In the northeastern region, for example, the sediments on the reefs of Rio do Fogo and Sioba, on the coast of the state of Rio Grande do Norte, have more than 55% of relict siliciclastic constituents (TESTA, 1997). Along the entire coast of the state of Bahia (the eastern region), on the nearshore reefs, 40 to 80% of the perireefal sediments have terrestrial sources (NOLASCO; LEÃO, 1986), particularly in the Abrolhos area (LEÃO; GINSBURG, 1997; BARROS; PIRES, 2006, DUTRA et al., 2006a; SEGAL; CASTRO, 2011). All of these siliciclastic sediments are unconsolidated muddy sands derived from ancient deposits that cover most of the hinterland and outcrops along the coast, mostly of the Tertiary Barreiras Formation that can also occur submerged on the inner shelf and, to a minor degree, from river outputs that are carried out to the reefs during winter storms. These environmental conditions, such as strong solar radiation, low light levels and high sediment influx, must exceed the tolerance levels of most of the Brazilian coral species. Only the most resistant and the best adapted species withstand the stressful conditions of our coastal waters.

Human-induced effects

Many coral reefs in the world are seriously threatened by anthropogenic action, particularly those located in embayments and near shallow shelves lying off densely populated areas, due to deforestation, intensive agriculture, urbanization and the consequent increases in the nutrient and sediment loads along with many other types of pollution. Additional human-associated factors that degrade coral reefs are overharvesting of reef organisms, destructive fishing methods, and uncontrolled tourism (GRIGG; DOLLAR, 1990; ROBERTS, 1995; DULVY et al., 1995; JENNINGS; POLUNIN, 1996).

The most common anthropogenic agents that threaten the coastal reefs of Brazil have been described in several publications, and they are directly related to coastal runoff and urban development, marine tourism, trading of reef organisms, predatory fishing, the installation of industrial projects, and the exploitation of fossil fuels (MAЎAL, 1986; COUTINHO et al., 1993; LEÃO, 1994; LEÃO et al., 1994; AMADO FILHO et al., 1997; MAIDA; FERREIRA, 1997, LEÃO et al., 2003). Although coral diseases were registered, for the first time, in the reefs from Abrolhos Bank only in 2005, they already represent a threat to the reefs in the region (FRANCINI-FILHO et al. 2008).

Coastal runoff

Although Brazilian coastal reefs have been coexisting with a muddy siliciclastic influx for a long time, they clearly, recently, have appeared to be under greater stress, primarily due to the increased coastal runoff. This increase can be attributed to the increasing deforestation of the Atlantic coastal rainforest for agricultural and industrial purposes, initially for sugar cane and coconut plantations, then to allow timber exploitation, and over the last few decades, to cultivate eucalyptus for industrial use. This rapid deforestation has significantly increased the runoff and the untreated sewage discharges from expanding urban centers, leading to abnormally high nutrient and algal growth at the expense of the corals. In the northeastern region, for example, the sugar cane monoculture forms a belt that is approximately 60 km wide and nearly 100 km long and located a few kilometers inland in the area in which the nearshore reefs are more numerous (MAIDA; FERREIRA, 1997). Along the eastern region, the effects of the increasing sedimentation rates are negatively correlated with the biotic parameters of the reef biota (DUTRA et al., 2006a, b; SEGAL et al. 2008; SEGAL; CASTRO, 2011), and the increase in the deposition of terrigenous mud near the inshore reefs over the last decades may significantly affect the reefs on the short term, even though the Brazilian coral fauna has already been surviving in turbid waters for a long time (SILVA et al., 2013).

Urban development

The unrestrained urban development in the coastal areas, primarily on the outskirts of the municipalities that already offer an infrastructure for tourism, with an extension of nearly 3,000 km along the Brazilian coast, is a potential threat to the reefs. The untreated urban garbage and organic sewage coming from those areas adjacent to the reefs is causing, in certain locations, an abnormal increase in the nutrients in the reef's biota, with dramatic consequences for the ecological balance of the environment. The measurements of the nutrient levels of the ground water of two villages along the coast of the state of Bahia, for example, show levels significantly higher than the normal conditions of the coastal waters (COSTA JR et al., 2000; 2006; COSTA JR, 2007). The influence of this enrichment in the nutrient levels caused by ground water contamination favors the activity of planktivorous macroborers (sponges and bivalves) in the nearshore reefs at levels that can be considered deleterious to the reefs due to the active bioerosion process which they promote (SANTA-IZABEL et al., 2000; REIS; LEÃO, 2003).

Marine tourism and overexploitation of reef organisms

Associated with the disorderly growth of the coastal towns and representing, in certain cases, the primary reason for their expansion, the marine tourism industry in Brazil has recently experienced extensive growth. The majority of the cities along the coast have been growing at the alarming rate of more than 1,000% over recent decades. The anchoring and beaching of boats, the scattering of litter, the movements of divers that either lean against or bump into the corals, and walking on the reef tops can damage the reefs. These activities, if not properly controlled, may have serious effects on the reef ecosystem. In the Abrolhos area, for example, only the reefs inside the limits of the Abrolhos National Marine Park are subject to a certain amount of control (SPANO et al., 2008). The reefs of the nearshore zone that comprise three-fourths of the total area of the reefs are not under any type of control (LEÃO et al., 1994). In addition to these reefs being located closer to the urban centers, there is no restriction to their recreational or commercial use, and they are subject to the highest fishing pressure in the entire region (FRANCINI-FILHO; MOURA, 2008; FRANCINI-FILHO et al., 2013). Several examples of reef areas explored by marine tourism have been registered in the literature, and they are already threatened. Certain examples in the northeastern region are the coral reefs along the coast of Maceio city in which the macrobenthic reef populations are reacting to the human effects caused by intense tourism (CORREIA; SOVIERZOSKY, 2010). On the Coral Coast of the state of Pernambuco, the marine tourism in the area of the coastal reefs is causing serious problems for the conservation of the reefs (MAIDA; FERREIRA, 2003; STEINER et al., 2006). Also in the State of Pernambuco, more recent studies of the reefs of Porto de Galinhas have observed a higher percentage of bare areas in which people are taken by boat to walk on the reef tops and practice snorkeling (BARRADAS et al., 2010, 2012). The demand for the reef animals as souvenirs and the aquarium trade has been intensifying in the reef areas throughout the length of the Brazilian coast. The corals have been being extracted for many years for the commerce of souvenirs in several areas of the reefs in the northeastern region (MAYAL, 1986). According to GASPARINE et al. (2005), Brazil is one of the five leading exporting countries of tropical aquarium fishes in the world, and the interest in marine ornamental organisms increased substantially from the mid to the late 1990s. In the Picãozinho reefs in the state of Paraiba, the trade in reef organisms, particularly of corals and fishes, is a common activity (ILLARI et al., 2007). In many coastal cities along the entire coast, particularly in the historical villages (i.e., in south Bahia), we can verify that for centuries, corals have been mined for building materials for the construction of old fortresses dating back to the 16th century and, currently, for the construction of rustic beach resorts.

The effects of ocean warming on the coral reefs

Coral bleaching events

Coral bleaching occurs when an environmental stress causes a disruption in the symbiotic relationship between the corals and their endosymbiotic algae zooxanthella (FITT, et al. 1993, MULLER-PARKER; D'ELIA, 1997). Because these microalgae living in the coral tissue provide a significant portion of the energy required by the coral to survive, when its photosynthetic pigments are expelled or lost during a prolonged or severe stress, partial or complete coral mortality may result (BROWN, 1997). In most registers of coral bleaching it is attributed to the abnormal increases in the temperature of the ocean waters (GLYNN, 1993, BROWN, 1997) which occur most frequently during El Niño events as, for example, during the events of 1982/83 (GLYNN, 1984), 1997/98 (WILKINSON, 2000), 2002/03 (BERKERMANS et al., 2004), 2005 (BRANDT, 2009; EAKIN et al., 2010) and, more recently, the strong and widespread event of 2010 when the coral reefs of several areas of the world were exposed to a higher magnitude of thermal stress (KRISHNAN et al., 2011, GUEST et al., 2012).

Most of the registered coral bleaching episodes have demonstrated that the effects of the thermal stress are a threat to the biodiversity and abundance of the coral reefs (WILKINSON, 2004; CARPENTER et al., 2008), also causing a negative effect on the growth of the coral species (EVANGELISTA et al., 2007).

The first registers of coral bleaching in Brazil occurred in the southern hemisphere summer of 1993/1994. An extensive bleaching of the species *Mussismilia hispida* and *Madracis decactis* occurred on the coast of the state of São Paulo (the southern region) (MIGOTTO, 1995) and in the area of the Abrolhos reefs (the eastern region) (CASTRO; PIRES, 1999). Regarding the São Paulo event, the author has cited an anomalous rise in the sea surface temperature as the major cause for the bleaching and has reported that after six months, all of the bleached colonies had recovered. On the northeastern coast, during the summer of 1996, bleached corals were observed during the months in which the ocean temperature reached values between 29ºC and 30ºC, but the corals recovered their normal colors when the water temperature returned to values between 26ºC and 28ºC (COSTA et al., 2001).

The strong El Niño event that began at the end of 1997 in the Pacific ocean caused a rise in the sea surface temperature in certain regions of the Brazilian coast as well. The sea temperature rise in Brazil started in mid-January 1998 (the summer in the southern hemisphere), attained its climax in mid-March and early April, and faded away at the end of May (data obtained from the Monthly Climatology Charts produced by Dr. Allan Strong, NOAA/NESDIS). During this period, a new bleaching event occurred in several sectors of the Brazilian coast, which were coincident with the oceanic thermal anomalies (KIKUCHI et al., 2003; LEÃO et al., 2003; KELMO et al., 2003; FERREIRA et al., 2006).

Between 2000 and 2010, severe coral bleaching events occurred in 2003, 2005 and 2010, all of which coincided with the period of the rising water temperature during El Niño. In the northeastern region during the event of 2003, approximately 30% of *Siderastrea stellata* colonies from the Cape Branco reefs in the state of Paraíba were affected (COSTA et al., 2001, AMORIM et al., 2011), and there are registers of bleached corals in the Rocas Atoll, the Fernando de Noronha Archipelago and from reefs along the coast of the state of Pernambuco (FERREIRA et al. 2006). For the eastern region, coral bleaching events were registered either in the summer of 2003 or that of 2005, but all of the corals recovered after the sea water temperature returned to its normal values (OLIVEIRA et al., 2007; LEÃO et al., 2008, 2009; KRUG et al., 2012, 2013). In 2010, the high sea surface temperatures that were recorded in several parts of the world as causing coral bleaching were also recorded in the Brazilian reef areas. In the Atol das Rocas and Fernando de Noronha Archipelago, the temperature anomaly reached 1.67ºC above average at the reef sites (FERREIRA et al., 2013). Along the coast of the state of Ceará, the first bleaching event recorded affected the corals *Siderastrea stellata* and *Favia gravida* and the zoanthid *Zoanthus sociatus* in an intertidal beachrock reef during the period of high sea surface temperatures (30ºC to 32ºC) for four to seven weeks (SOARES; RABELO, 2014). In the eastern region, severe coral bleaching affected the reef areas along the coast of the state of Bahia when thermal anomalies of up to 1ºC were recorded (MIRANDA et al., 2013, KIKUCHI et al., 2013) (Figure 13).

Figure 13. Photograph of bleached corals along the eastern coast of Brazil during the 2010 El Niño event. (Photo courtesy of R. Miranda).

Considering all the registers of coral bleaching in Brazil prior to 2005, the studies of KRUG et al. (2012) and the model developed by KRUG et al., (2013) show that the bleaching events in the eastern region, are strongly related to occurrences of sea surface temperature anomalies. Although, in most of cases, bleaching had affected several reef areas with great intensity, prior to the 2010 event, no episodes of coral mass mortality had been recorded (KIKUCHI et al., 2010; LEÃO et al., 2008, 2010; KRUG et al., 2012, MIRANDA et al., 2013; KIKUCHI et al., 2013; FERREIRA et al. 2013).

How to evaluate and mitigate the effects on the Brazilian coral reefs

Although the Brazilian coral fauna has shown resistance to bleaching and mortality and may be functionally adapted to the stressful condition of the highly turbid coastal waters, a synergism of these processes with the current anthropogenic disturbances can aggravate the recovery capacity of this already disturbed coral community. Improvements in protective measures should be enforced in the existing Brazilian Conservation Units, identifying priorities for action, such as campaigns to change people's attitude towards reef conservation, to strengthen monitoring programs and the value of reef assessment and to demonstrate the need for and effectiveness of management practices to decision-makers.

Protection and Management

Scientific information about the coral reefs in Brazil has existed for over a century; however, knowledge as to the actual condition of the reefs in terms of their protection is scarce, and for certain areas, was virtually unknown until recently, when an initiative of the Directorate of Protected Areas of the Brazilian Ministry of Environment (DAP-MMA) developed a project for the conservation of the coral reefs, expending effort in mapping the shallow reefs found in the existing Conservation Units. This "Atlas of Coral Reef Protected Areas of Brazil" provides a considerable increase in the useful information available, especially regarding monitoring of the reefs and the preparation or updating of management plans for the Conservation Units (PRATES, 2006).

The Conservation Units are distributed along the entire coast of Brazil and include nearly all of the country's oceanic islands, with different management categories at the following three levels of government: federal, state and municipality (PRATES; PEREIRA, 2000). Two of the nine existing Conservation Units, at the time when the Atlas was prepared, were on oceanic islands, the Biological Reserve of Atol das Rocas and the National Marine Park of Fernando de Noronha (both of these were designated as Natural World Heritage Sites in 2001); three were on the limits of reef distribution, in the State Marine Park of Parcel de Manuel Luiz, in the state of Maranhão (designated a Ramsar Site in 2000), the National Marine Park of Abrolhos and the State Environmental Protection Area of Ponta da Baleia, both in the state of Bahia. The remaining four were on more coastal areas, as follows: the State Environmental Protection Area of Recifes de Corais in the state of Rio Grande do Norte, the Environmental Protection Area of Costa dos Corais in the states of Pernambuco and Alagoas, the Municipal Marine Park of Recife de Fora, in the state of Bahia, and the Marine Extractive Reserve of Corumbau, also in the state of Bahia (PRATES, 2006). In a second initiative of the DPA-MMA, the "Coral Reef Conservation Campaign", seven other Conservation Units were added to the list, as follows: the Environmental Protection Area of Fernando de Noronha, Rocas and São Pedro, São Paulo, the State Marine Park of Areia Vermelha, in the state of Paraiba, and the Environmental Protection Area of the Baía de Todos os Santos, the Environmental Protection Area of the Recife das Pinaunas, the Environmental Protection Area of Tinharé-Boipeba, the Marine Municipal Park of Coroa Alta and the Marine Municipal Park of the Recife da Areia, all of which are in the state of Bahia. The primary purpose of the Coral Reef Conservation Campaign is to increase the awareness of the various users of the coral reef areas as regards the importance and fragility of these environments, disseminating rules for responsible conduct to preserve these areas in their original state, in view of the fact that coral reefs are one of the most endangered ecosystems in the world (PRATES et al., 2002).

Concurrent with the official initiatives, every citizen (including divers, fishermen, tourists, businessmen, government officials, teachers, students, scientists, among others) should take preventive measures to protect the reefs. These measures may include personal ones, involving the choice of a proper place to anchor, suitable handling of garbage, avoiding the collection of living corals or any other reef organisms, reducing marine pollution, habitat degradation and destructive fishing practices, and supporting or participating in the actions of groups, organizations or companies concerned with the protection of coral reefs. To ensure that the coral reefs will continue to exist for future generations, we must reduce the greenhouse gases that are warming and acidifying the ocean. These attitudes will establish the critical levels of the effects on the reef communities, will permit a better understanding of the Brazilian coral reefs, and will provide support for their effective management.

Reef Monitoring and Assessment

The effective management responses depend on the availability of adequate information and its evaluation.

This process will become possible through monitoring programs that cover all the aspects related to the essential components of the ecosystem, providing real-time information. Long-term monitoring programs, at protected and unprotected sites, will make possible the construction of a consistent view of reef decline associated with information on the environmental conditions related to the major degradation events. To monitor the coral reefs, the Global Coral Reef Monitoring Network (GCRMN) has adopted several monitoring protocols, which have been used in different regions around the globe to evaluate the health and dynamics of the reef environment. Many of these protocols are comparable because the evaluation methods are similar.

In Brazil, several methods have been used to evaluate the coral reefs. Two of the methods that were adopted by certain participants of the ReBentos are included in the GCRMN, as follows: the Reef Check (FERREIRA et al. 2006) and the Atlantic and Gulf Rapid Reef Assessment (AGRRA Version 5.4; LANG et al., 2010). These two programs already have data from reef assessment spanning more than 10 years. To compare the condition of the reefs along the entire tropical coast, components of the Coral Reef Work Group of the INCT AmbTropic (National Institute of Science and Technology for the Tropical Marine Environments) and of the ReBentos have developed a Field Protocol, which includes the common points from the various methods that have hitherto been used. The objective of the Protocol is to assess the vulnerability, resilience and resistance of the coral reef ecosystems in Brazil that are facing the effects of anthropogenic and climate change and to generate information on the health and demographic connectivity between the reefs, which is important information for the adoption of effective management and conservation tools. A comparison of the spatial-temporal variations observed in the coral reef ecosystems of the continental shelf and the oceanic islands is intended to determine and understand the capacity of these ecosystems to withstand and recover from disturbances of different degrees of intensity in view of the spatial heterogeneity characterized by morphological, structural and compositional differences of the reefs and the «health» of the protected systems and those most exposed to threats. As indicators for the assessment of the condition of the reefs, the protocol will use the corals and reef fishes. For the corals, the protocol will use the following: richness and diversity, the relative reef area covered by living corals, percentage of bleaching, colonies affected by diseases, recent and old mortality and the density of the coral recruits. For the fishes, the protocol will use the following: density, richness and diversity per family and per group (herbivores, carnivores and omnivores) and measurements of their size. The relative coverage of the functional groups of algae (macro, coralline, and turf), sponges, zoanthids, sea urchins and other organisms considered important for the reefs investigated will also be considered (LEÃO et al. 2015). We hope that in the near future we shall be in possession of an accurate assessment of the condition of Brazilian coral reefs.

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Rhodoliths in Brazil: Current knowledge and potential impacts of climate change

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Abstract

Rhodolith beds are important marine benthic ecosystems, representing oases of high biodiversity among sedimentary seabed environments. They are found frequently and abundantly, acting as major carbonate 'factories' and playing a key role in the biogeochemical cycling of carbonates in the South Atlantic. Rhodoliths are under threat due to global change (mainly related to ocean acidification and global warming) and local stressors, such as fishing and coastal run-off. Here, we review different aspects of the biology of these organisms, highlighting the predicted effects of global change, considering the additional impact of local stressors. Ocean acidification (OA) represents a particular threat that can reduce calcification or even promote the decalcification of these bioengineers, thus increasing the eco-physiological imbalance between calcareous and fleshy algae. OA should be considered, but this together with extreme events such as heat waves and storms, as main stressors of these ecosystems at the present time, will worsen in the future, especially if possible interactions with local stressors like coastal pollution are taken into consideration. Thus, in Brazil there is a serious need for starting monitoring programs and promote innovative experimental infrastructure in order to improve our knowledge of these rich environments, optimize management efforts and enhance the needed conservation initiatives.

Descriptors: Algae, Conservation, Brazil, Global warming, Pollution, Ocean acidification.

Resumo

Bancos de rodolitos formam oásis de alta biodiversidade em ambientes marinhos de fundo arenoso. Os rodolitos são formados por espécies bioconstrutoras, que fornecem abrigo e substrato para diversas e abundantes comunidades bentônicas. No Brasil esses ambientes são frequentes, representando grandes "fábricas" de carbonato com um papel fundamental no ciclo biogeoquímico do carbono no Atlântico Sul. Estes organismos e ambientes estão ameaçados pelas mudanças climáticas (principalmente a acidificação dos oceanos e o aquecimento global) e pelos estressores locais, tais como os impactos causados pela pesca e as descargas costeiras de efluentes. Neste trabalho fazemos uma revisão da taxonomia, filogenia e biologia desses organismos, com destaque para os efeitos previstos das mudanças climáticas e suas relações com estressores locais. A maioria dos estudos acerca dos efeitos das mudanças climáticas e da acidificação dos oceanos em algas calcárias relatam respostas negativas não só no crescimento e na calcificação, mas também no processo de fotossíntese, espessura da parede celular, reprodução e sobrevivência das algas. Este cenário reforça a necessidade em estabelecer uma consistente rede de trabalho para proporcionar um programa de monitoramento amplo e de longo prazo, bem como infraestrutura para avaliações experimentais de impactos locais e regionais das mudanças climáticas e dos estressores locais em bancos de rodolitos.

Descritores: Algas, Conservação, Brasil, Mudanças climáticas, Poluição, Acidificação dos oceanos

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INTRODUCTION

Pink or red "rocks" on the sea floor often consist of different morphotypes of a particular kind of calcareous red algae (Corallinophycidae). This particular kind of seaweed, known as coralline red algae, present calcium carbonate impregnated (i.e. calcified) cell walls. Crustose coralline red algae are completely calcified encrusting organisms (Figure 1) that either adhere tightly to hard substratum or remain unattached to the seafloor (BROOM et al., 2008). Rhodoliths (including maërl) can be defined as calcareous nodules composed of more than 50% of coralline red algal material and consisting of one to several coralline species growing together (BOSELLINI; GINSBURG, 1971). They may cover extensive areas of the seafloor forming large beds, often associated with high marine biodiversity (STELLER et al., 2003; RIUL et al., 2009; PEÑA et al., 2014). Rhodoliths may be composed entirely of encrusting coralline algae or may have a core of non-coralline material (e.g. a shell, piece of dead coral or a pebble), in addition to encrustations by other calcified organisms. They are distributed worldwide (FOSTER, 2001), from tropical to polar regions (ADEY; STENECK, 2001), and from the intertidal zone to depths of 268 m (LITTLER et al., 1986). Rhodolith beds represent one of the largest carbonate depositional environments in the world (TESTA; BOSENCE, 1999), which makes them an important component in the global carbon biogeochemical cycle and hence, in the atmospheric CO_2 balance (OLIVEIRA, 1996).

In Brazil, rhodolith beds extend over almost the entire continental shelf from Maranhão (0° 50'S) to Santa Catarina state (27°17'S). They predominate within the mesophotic zone (~ 30-150 m depth) along the continental shelf, on the tops of seamounts, and around oceanic islands (AMADO-FILHO; PEREIRA-FILHO, 2012). The mesophotic coralline ecosystems represent extensions of shallower ecosystems (HINDERSTEIN et al., 2010), however, information on biotic and abiotic aspects of mesophotic habitats remains extremely scarce, due to logistic and technological restrictions, when compared to shallow habitats (BRIDGE et al., 2011). However, recent advances in mixed-gas diving techniques, complemented by ROV observations, and high-resolution multi-beam bathymetric mapping systems allow us to begin determining rhodolith beds' extent, structure, and dynamics (FOSTER et al., 2013).

Rhodoliths represent heavily calcified organisms, depositing calcium carbonate in the form of high Mg-calcite, a mineral that attains up to ~90 % of the dry weight of these species (WOELKERLING, 1993; OLIVEIRA, 1997) and ensures good preservation in fossil record. These features call the attention not only of phycologists, but also palaeontologists and geologists interested in the carbonate abundance of limestone deposits found since the Cretaceous (LITTLER, 1972; BASSO, 2012). It has been estimated that the Brazilian continental shelf carbonate stock holds 2 x 10^{11} tonnes of $CaCO_3$ (MILLIMANN; AMARAL, 1974). Among the rhodolith beds along the Brazilian coast, the Abrolhos shelf boasts the world's largest expansion of rhodoliths in the Atlantic, with a mean relative cover of rhodoliths around 69.1% (± 1.7%) and a mean density of 211 ± 20 nodules per square meter (AMADO-FILHO et al., 2012a). These authors estimated a mean $CaCO_3$ production rate of about 0.025 Gt/year for the Abrolhos shelf, containing approximately 5% of the $CaCO_3$ inventory of all the world's carbonate banks. In addition to its importance in the global carbon cycle (VAN DER HEIJDEN; KAMENOS, 2015), the reported amount of limestone has also called the attention of multinational companies interested in the large-scale exploitation of these deposits for agronomic purposes. However, the relatively low growth rate of mesophotic rhodoliths (about 1.0 mm per year, BLAKE; MAGGS, 2003; AMADO- FILHO et al., 2012a) confers on this resource a nearly non-renewable characteristic, at least on human time-scales (WILSON et al., 2004). In addition to the use of rhodolith beds as a source of $CaCO_3$, other potential economic uses include exploiting their associated biodiversity as a source of bioactive compounds in the pharmacology, agriculture and nutraceutical industries (AMADO-FILHO; PEREIRA-FILHO, 2012; MARINS et al., 2012).

Despite their great importance for biodiversity resilience and the global carbon budget, in Brazil the functional ecology of these complex habitats, considering the intrinsic latitudinal and vertical variability, has received relatively little attention. In contrast, research programs and initiatives in Europe (e.g. BIOMAERL, 1996-1999; United Nations Environment Programme, UNEP, 2007, 2015) have contributed to the knowledge of: (1) rhodolith bed diversity, (2) rhodolith-bed associated biota, (3) functional roles played by key elements of the biota, and (4) impacts of anthropogenic stressors. This information is being used to establish research and conservation priorities for European rhodolith-dominated communities, and to suggest how these may be achieved.

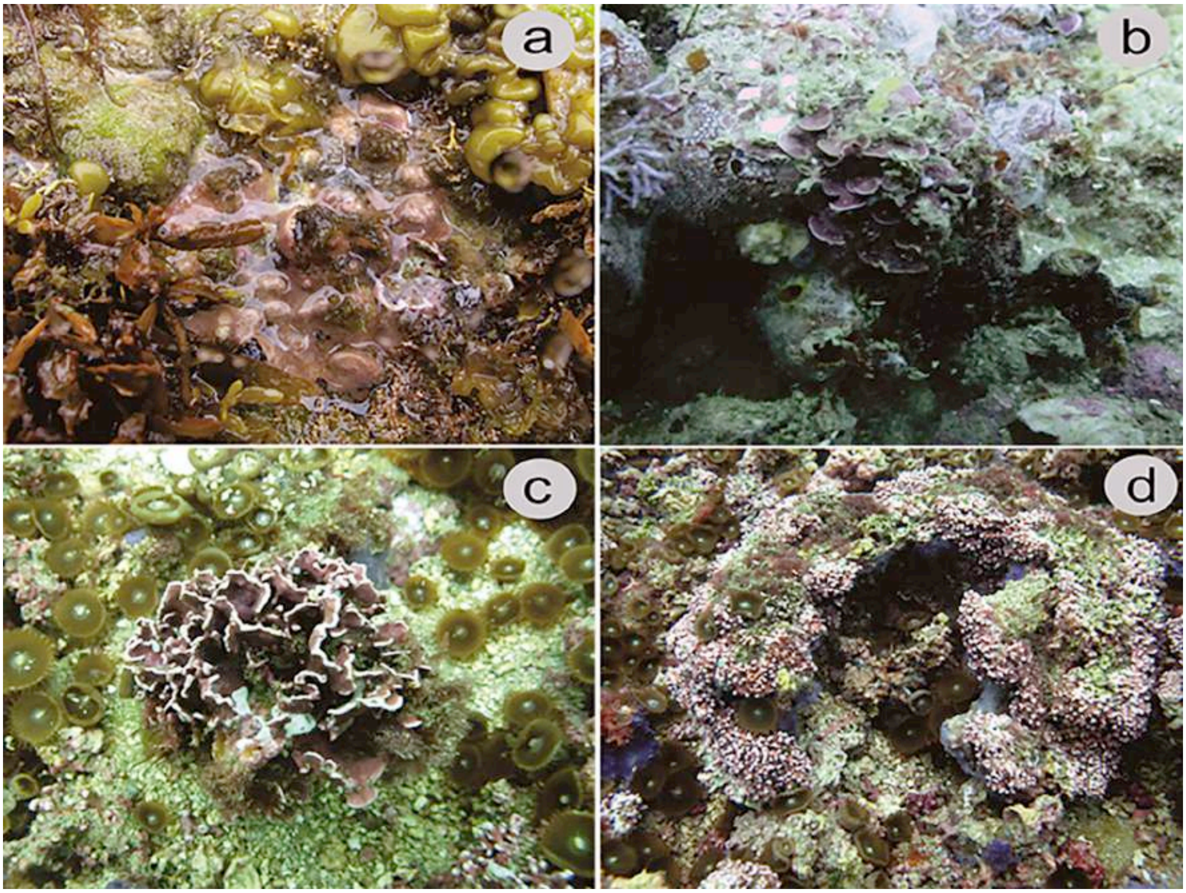

Figure 1. Diversity of coralline red algal forms. (a) Encrusting form in the intertidal zone; (b) prostrate foliose form; (c) erect foliose rhodolith; (d) fruticose rhodolith. Photos: M.N. Sissini.

In Brazil, only in the last decade have rhodolith beds started gaining more prominence with an increase in the number of published studies on community structure, habitat mapping, the influence of anthropogenic impacts, and molecular systematics (see Table 1).

In the light of the great ecological and economic importance of rhodoliths, the range of threats they face currently, as well as those they will face in the future, and the lack of knowledge on the extent of their distribution and diversity in Brazil, the present bibliographical review aims to provide the basic information necessary to guide future studies, particularly those related to global climate change and its interaction with local stressors.

Ecological role

Rhodolith beds provide significant changes in the physiognomy of benthic communities, compared to those in the surrounding sandy bottom environments (Figure 2; FOSTER et al., 2013). The rhodolith-bed forming species are considered ecosystem engineers (HALFAR; RIEGL, 2013) and their growth and accumulation over geological time have constituted important sedimentary deposits (DIAS, 2000). They can also be considered key species because their thallus shape and skeletal stability promote structural changes in the environment, increasing habitat heterogeneity and niche availability, resulting in increased species diversity (STELLER et al., 2003; FOSTER et al., 2013). In general, higher species diversity is attributed to the greater availability of refuges and other resources that reduce losses derived from competitive exclusion, predation, and physical disturbance events. For these reasons rhodolith beds have been proposed as one of the most valuable habitats for studies on marine biodiversity both in Europe (BARBERA et al., 2003) and in Brazil (HORTA et al., 2001).

Taxonomy and morphology

Rhodoliths comprise the third most diverse group within the Rhodophyta, with approximately 600 recognized

Table 1. Summary of published studies on Brazilian rhodolith beds.

Main focus	References
Meso- and small-scale distribution	AMADO-FILHO et al. (2007, 2012a) RIUL et al. (2009) PEREIRA-FILHO et al. (2011, 2012) MOURA et al. (2013)
Rhodolith bed structure	TESTA; BOSENCE (1999) GHERARDI (2004) AMADO-FILHO et al. (2007) RIUL et al. (2009) BAHIA et al. (2010) PASCELLI et al. (2013)
Contribution to global carbonate production	BRASILEIRO et al. (2015) KEMPF (1970) MILLIMAN; AMARAL (1974) MELLO et al. (1975) AMADO-FILHO et al. (2012a)
Species composition of rhodolith beds	TESTA (1997) HORTA (2002) AMADO-FILHO et al. (2007) NUNES et al. (2008) FARIAS (2010) VILLAS-BÔAS et al. (2009, 2014a) BAHIA et al. (2010, 2014) FIGUEIREDO et al. (2012) CRESPO et al. (2014) TORRANO-SILVA et al. (2014) HENRIQUES et al. (2014 a and b) VIEIRA-PINTO et al. (2014) COSTA et al. (2014) BORGES et al. (2014) SISSINI et al. (2014)
Associated communities/organisms	BAHIA et al. (2015) TAMEGA et al. (2015) FIGUEIREDO et al. (1997) GHERARDI & BOSENCE (2001) ROCHA et al. (2005) FIGUEIREDO et al. (2007) METRI & ROCHA (2008) AMADO-FILHO et al. (2010) SCHERNER et al. (2010) PEREIRA-FILHO et al. (2011) SANTOS et al. (2011) AMADO-FILHO & PEREIRA-FILHO (2012) BERLANDI et al. (2012) PASCELLI et al. (2013) GONDIM et al. (2014) VILLAS-BÔAS et al. (2014a) PEREIRA-FILHO et al. (2015)
Influence of environmental factors on rhodolith bed habitats	MEIRELLES et al. (2015) RIUL et al. (2008) MARINS et al. (2012) VILLAS-BÔAS et al. (2014b) FIGUEIREDO et al. (2015)

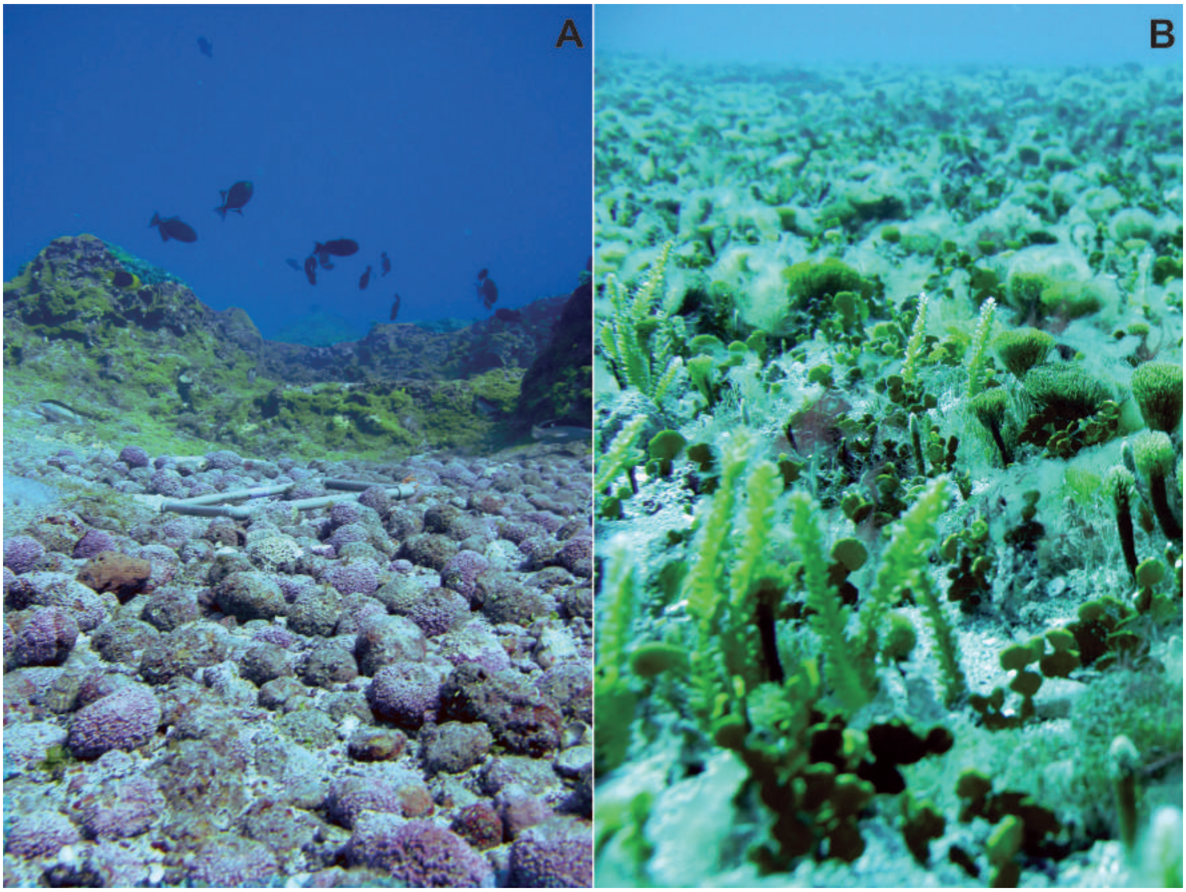

Figure 2. Different rhodolith physiognomies are sometimes observed at a single site, such as on Trindade Island. (A) Rhodolith beds without abundant associated benthic flora and (B) rhodolith beds with abundant overgrowth of other algal species. Photos: M.N. Sissini.

morpho-species (BRODIE; ZUCCARELLO, 2007; GUIRY; GUIRY, 2015). To date, 48 species of encrusting coralline red algae have been recognized in the Brazilian flora: 9 Sporolithaceae, 25 Corallinaceae, and 14 Hapalidiaceae (Table 2). Of those, about 26 species are known, on the Brazilian coast, as rhodolith-forming. In relation to habitat or morphotype, there are no studies distinguishing between the occurrence of exclusively rhodolith-forming or exclusively non-rhodolith-forming species.

Because rhodolith beds consist of a diversity of living organisms, they are characterized as being both temporally and spatially dynamic ecosystems (AMADO FILHO et al., 2010; BARRETO, 1999; DIAS, 2001; DIAS; VILLAÇA, 2012). The surface morphology of rhodoliths presents variations regulated by depth (ADEY et al., 1982), hydrodynamic bioerosive processes and taxonomy (BOSENCE, 1983). Depth is also a regulatory factor for rhodolith density (m^{-2}) and size (Figure 3; BAHIA et al., 2010; PASCELLI et al., 2013). A comparison of three areas of the Brazilian tropical continental shelf with contrasting slopes showed that in areas with a gentle slope, rhodoliths increased in size and decreased in abundance (m^{-2}), with a gentle increase of the ellipsoidal to spherical shape with depth (BAHIA et al., 2010). In contrast, rhodoliths from narrow shelves and steep slopes decreased in size but increased in abundance.

Studies have also noted that the number and size of protuberances, hollows or cavities that characterize different morphotypes of rhodoliths are fundamental features that determine the diversity and abundance of the associated flora and fauna (e.g., AMADO-FILHO et al., 2010; BERLANDI et al., 2012). All this morphological plasticity makes the taxonomical evaluation of their diversity difficult, particularly at the species level.

Associated fauna and flora

In some large areas of the Brazilian coast, the lack of hard substrate prevents the occurrence of most macroalgal species. In these areas rhodolith beds provide habitats for fleshy macroalgae and other groups of benthic organisms,

Table 2. Species of Corallinophycidae (excluding articulate forms) reported for the Brazilian coast. (* indicates the species that still need to be revised using modern techniques and nomenclature; ◦ indicates the species that have been added in the last three years; # indicates rhodolith-forming species).

SPOROLITHALES
Sporolithaceae
Sporolithon australasicum (Foslie) N. YAMAGUISHI-TOMITA EX M.J. WYNNE*
Sporolithon elevatum HENRIQUES & RIOSMENA-RODRIGUEZ◦#
Sporolithon episporum (M.A. Howe) E.Y. DAWSON #
Sporolithon erythraeum (Rothpletz) KYLIN*
Sporolithon howei (Lemoine) N. YAMAGUISHI-TOMITA EX M.J. WYNNE*
Sporolithon molle (Heydrich) HEYDRICH◦#
Sporolithon pacificum E.Y. DAWSON*
Sporolithon ptychoides HEYDRICH◦#
Sporolithon tenue BAHIA, AMADO-FILHO, MANEVELDT and W.H. ADEY◦#
CORALLINALES
Coralinaceae
Hydrolithon boergesenii (Foslie) FOSLIE
Hydrolithon farinosum (J.V. Lamouroux) D. PENROSE and Y.M. CHAMBERLAIN
Hydrolithon rupestre (Foslie) PENROSW◦#
Hydrolithon samoënse (Foslie) KEATS and Y.M. CHAMBERLAIN
Lithophyllum atlanticum VIEIRA-PINTO, OLIVEIRA and HORTA◦#
Lithophyllum congestum (Foslie) FOSLIE◦
Lithophyllum corallinae (P.L. Crouan and H.M. Crouan) HEYDRICH#
Lithophyllum depressum VILLAS-BOAS, FIGUEIREDO and RIOSMENA-RODRIGUEZ#
Lithophyllum johansenii WOELKERLING and CAMPBELL#
Lithophyllum margaritae (Hariot) HEYDRICH◦#
Lithophyllum stictaeforme (Areschoug) HAUCK#
Neogoniolithon accretum (Foslie and Howe) SETCH and MASON
Neogoniolithon atlanticum TÂMEGA, RIOSMENA-RODRIGUEZ, MARIATH and FIGUEIREDO◦
Neogoniolithon brassica-florida (Harvey) SETCHELL and MASON◦
Neogoniolithon fosliei (Heydrich) SETCHELL and MASON#
Neogoniolithon mamillare (Harvey) SETCHELL and MASON*
Pneophyllum conicum (Dawson) KEATS, CHAMBERLAIN and BABA◦
Pneophyllum fragile KÜTZING*#
Porolithon improcerum (Foslie and Howe) LEMOINE◦
Porolithon onkodes (Heydrich) FOSLIE
Porolithon pachydermum (Foslie) FOSLIE◦
Spongites fruticulosa KÜTZING◦#
Spongites yendoi (Foslie) CHAMBERLAIN◦#
Titanoderma prototypum (Foslie) WOELKERLING, Y.M. CHAMBERLAIN and P.C. SILVA◦#
Titanoderma pustulatum (J.V. Lamouroux) NÄGELI#
HAPALIDIALES
Hapalidiaceae
Lithothamnion brasiliense FOSLIE*#
Lithothamnion crispatum HAUCK◦#
Lithothamnion glaciale KJELLMAN◦#
Lithothamnion muelleri LENORMAND ex ROSANOFF◦#
Lithothamnion occidentale (Foslie) FOSLIE#
Lithothamnion sejunctum FOSLIE
Lithothamnion steneckii MARIATH and FIGUEIREDO◦
Melobesia membranacea (Esper) J.V. LAMOUROUX
Melobesia rosanoffii (Foslie) LEMOINE◦
Mesophyllum engelhartii (Foslie) ADEY◦#
Mesophyllum erubescens (Foslie) Me. LEMOINE#
Mesophyllum macroblastum (Foslie) W.H. ADEY◦
Phymatolithon calcareum (Pallas) W.H. ADEY and D.L. MCKIBBIN*#
Phymatolithon masonianum WILKS and WOELKERLING

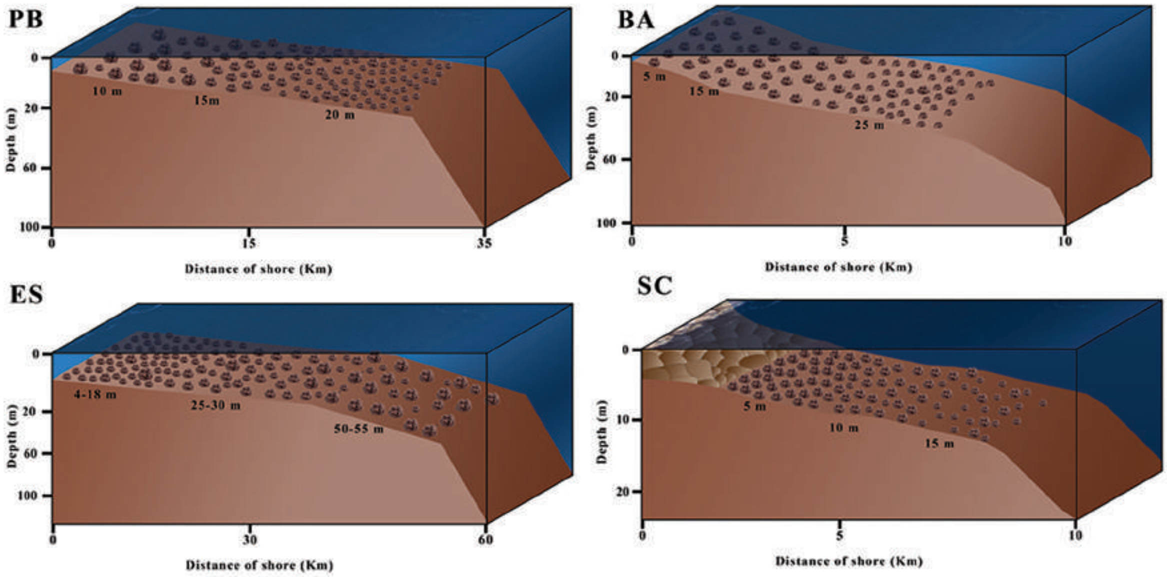

Figure 3. Vertical and latitudinal changes observed in the size (volume) and density of rhodoliths from different beds on the Brazilian coastline (based on BAHIA et al., 2010 and PASCELLI et al., 2013). PB: Paraíba; BA: Bahia; ES: Espírito Santo; SC: Santa Catarina.

thus increasing local biodiversity (RIUL et al., 2009) and primary production. Biodiversity, productivity and live biomass (standing stock) in shallow rhodolith beds are higher than in most of their equivalents found in deeper areas or in unconsolidated flat bottom communities (RIUL et al., 2009). Remarkably, rhodolith beds provide refuge for small animals, as abundant mesograzers in southern Brazil (SCHERNER et al., 2010), and many larger species of fish and invertebrates that occur on adjacent reef systems will pass over these beds, looking for food and substrate for reproduction. Despite such limitations in supporting a ‟complete" reef assemblage, rhodolith beds likely represent migration corridors for several species when they cover large inter-reef areas, such as those found in the Abrolhos Bank (AMADO-FILHO et al., 2012a). When compared to deep-water sand and mud-benthic communities, rhodolith beds represent submerged oases (Figure 4). In this context, PEREIRA-FILHO et al. (2015) hypothesized that the coalescence of rhodoliths constitutes an early successional stage in the formation of large coralline reefs on southwestern Atlantic tropical shelves.

In a study evaluating the marine biota of the Brazilian Exclusive Economic Zone, LAVRADO (2006) reported a Shannon-Wiener diversity index of 4.0 and 5.1 for specific areas down to 250 m depth and associated this increase in the diversity of epibenthic communities to the presence of rhodolith beds. Information about density, dimension, shape and percentage of the live surface of rhodoliths, associated fauna and flora, rhodolith growth rates, and calcium carbonate mineralization for specific areas of the Brazilian Economic Exclusive Zone.

PEREIRA-FILHO et al. (2012) and AMADO-FILHO et al. (2012b) showed that the mesophotic zone of seamount tops and insular shelves of oceanic islands present rich benthic communities dominated by rhodoliths. Despite their extensive area, the fauna and flora richness associated with rhodolith beds in Brazil is very poorly studied and research has focused on few specific sites and taxa (Figure 5). However, the importance of rhodolith beds in supporting a high diversity and abundance of marine species in comparison with surrounding habitats is recognized (NELSON, 2009), and at least one endemic species, the polychaete *Sabellaria corallinea*, is known to occur only in the rhodolith beds of northeastern Brazil (SANTOS et al., 2011).

In the few studies that have evaluated the fauna associated with rhodolith beds, 136 solitary and 32 colonial species of invertebrates, totalling 168 taxa, have been reported growing in 100 m^2 of a subtropical rhodolith bed located on Arvoredo Island, southern Brazil (METRI; ROCHA, 2008). Among the solitary forms, Polychaeta, Crustacea and Mollusca were the most important groups, while among the colonial forms the Porifera *Pachataxa* sp. and the Ascidiacea *Didemnum* sp. were registered in 90% of the samples. Another study by BERLANDI et al. (2012) compared the Polychaeta composition of different

Figure 4. Example of the seaweed and zoobenthic communities found in rhodolith beds on the Brazilian coast. This picture highlights the presence of gastropods, echinoderms and a turf algae assemblage on Desert Island, southern Brazil. Photo: P.A. Horta.

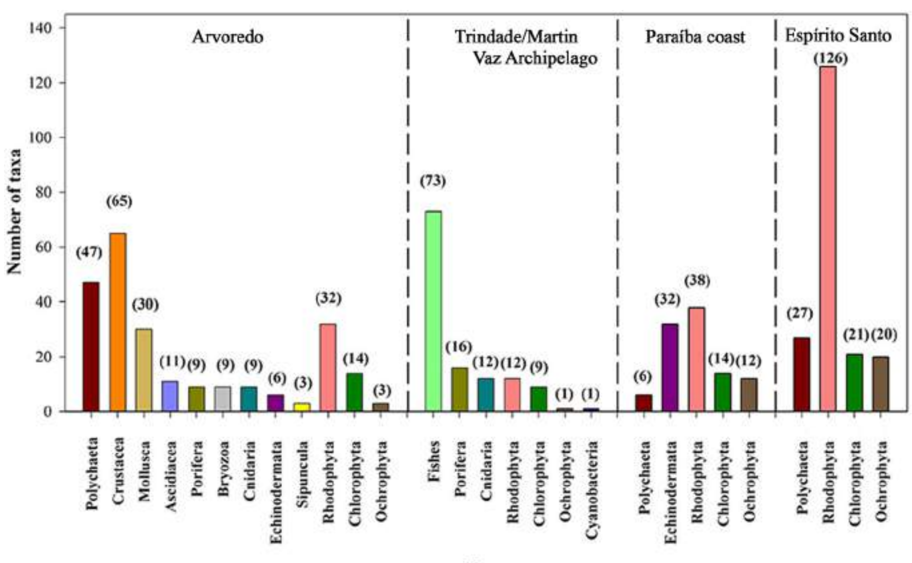

Figure 5. Fauna and flora associated with Brazilian rhodolith beds. Arvoredo Island, according to BOUZON & FREIRE (2007), MERTI & ROCHA (2008), SCHERNER et al. (2010) and PASCELLI et al. (2013), Trindade and Martin Vaz Island according to PEREIRO-FILHO et al. (2011), rhodolith beds off the coast of Paraíba according to RIUL et al. (2009), SANTOS et al. (2011) and GONDIM et al. (2014), and Espírito Santo according to FIGUEIREDO et al. (2007), AMADO-FILHO et al. (2010) and BERLANDI et al. (2012). Numbers indicate the number of species described for the taxa and the same color was used for the same taxa at each site.

rhodolith forms (small rhodoliths with long branches and large rhodoliths with short branches) and found that of the 26 families that had been found, 4 were exclusively associated with large rhodoliths and 9 exclusively with the small ones. The rhodolith-bed associated fauna and flora have been studied almost exclusively in beds found above 30 m.

In relation to the rhodolith-bed associated flora, some studies have indicated a high and specific diversity. For example, AMADO-FILHO et al. (2010) reported that in the southern part of Espírito Santo state rhodolith beds provide an important habitat for epibenthic communities, supporting 25% of the known macroalgal species richness along the Brazilian coast. Also, new records of seaweeds have been found specifically associated with the rhodolith beds of Espírito Santo and the northeastern and southeastern Brazilian coasts (AMADO-FILHO et al., 2010, GUIMARÃES; AMADO-FILHO, 2008; RIUL et al., 2009).

Global and local threats

Rhodolith beds, like many other marine ecosystems, are affected by ongoing global change due to the rise in the concentration of greenhouse gases in the atmosphere (CO_2 in particular) and all its associated consequences, such as an increase in seawater temperatures (1-4°C by 2100), decreases in seawater pH (by ~0.3-0.5 units), shifts in carbon chemistry, sea level rise, and the increase in the strength and frequency of extreme weather events (GIBBARD et al., 2005; IPCC, 2014).

Global change is likely to have a profound impact on the physiology of a range of marine species across many phyla. However, warmer seawater temperatures and ocean acidification (OA) are expected to have a stronger negative effect on crustose coralline species, such as most rhodolith species, than on other macroalgal taxa (DONEY et al., 2009). Data from multiple mesocosm studies on the effect of OA and/or temperature rise on different species of macroalgae suggest that the magnitude of algal growth and calcification responses to OA seems to be species-specific (e.g. PRICE et al., 2011; JOHNSON et al., 2012; CAMPBELL et al., 2014). However, as a general rule, most calcareous algae seem to experience a reduction in biomineralization, while non-calcareous algae either show no effect or become more productive (DONEY et al., 2009; JOHNSON et al., 2012; KROEKER et al., 2012).

Calcified organisms can also act as buffers to OA, since they release CO_3^{2-} ions that bind with free H^+ protons to form HCO_3^-, thus neutralizing the acidification process (DONEY et al., 2009; SABINE; TANHUA, 2010; BASSO, 2012). Model predictions estimate that in the future seawater CO_2 concentration will increase by 192% and HCO_3^- will increase by 14% from de-calcification processes (ROLEDA et al., 2012). These changes are expected to cause negative effects on marine calcifiers, both animals and algae, due to their reduced ability to maintain and/or renew their calcareous skeleton (FABRY et al., 2008; JOKIEL et al., 2008; TYRRELL, 2008; HURD et al., 2009; RUSSELL et al., 2009; SEMESI et al., 2009; CORNWALL et al., 2012; JOHNSON et al., 2012). Despite the prediction that OA can compromise calcification, this process depends on the particularities of the physiology and mineralogy of the different taxonomic groups (RODOLFO-METALPA et al., 2009).

As regards the two main crystallographic forms of biological carbonates, aragonite is twice as soluble as pure calcite, while calcite with high Mg concentrations (8-12%) is more soluble than aragonite (MORSE et al., 2006). Changes in the chemistry of seawater or increased temperatures can change the Mg content in the calcification process, altering the solubility of these crystals and eventually enhancing the sensitivity of calcifiers to OA (AGEGIAN, 1985; see review BASSO, 2012). However, it has been shown that coralline algae are able to form dolomite (NASH et al., 2012; DIAZ-PULIDO et al., 2014), a feature that has been associated with organisms living in high-energy environments (NASH et al., 2013). This mineral, formed within the cell wall, provides potential stability to calcareous algae, as inferred from the geological record. In fact, a recent study has shown that coralline algae exposed to OA and conditions of increasing warmth increased their dolomite concentration by 200% (DIAZ-PULIDO et al., 2014). Dolomite-rich coralline red algae have 6-10 times lower rates of dissolution than those precipitating predominantly Mg-calcite (NASH et al., 2013). This property must be responsible for its abundance during periods of high CO_2 concentration in our geological past and represents an important aspect that should be taken into consideration when considering experiments about OA.

For many photosynthetic marine organisms, changes in CO_2 availability may either have no effect or may alter their metabolism in either positive or negative ways (see review KOCH et al., 2013). For example, species whether without or with inefficient carbon concentration mechanisms are usually carbon limited. For these organisms, higher pCO_2 increases the affinity of RUBISCO for CO_2, with a consequent increase in their photosynthetic rates (see review KOCH et al., 2013). In the case of coralline algae, they that are considered to be one of the groups of calcifying taxa with the highest susceptibility to OA, as they accrete high-Mg calcite, the most soluble form of $CaCO_3$. (BOROWITZKA, 1982; MORSE et al., 2006). The $CaCO_3$ deposition in this algal group occurs extracellularly within the cell wall (see review in BOROWTZKA, 1982), representing up to 80-90% of their biomass (BILAN; USOV, 2001).

Most studies about the OA effect on coralline algae report negative responses in growth and calcification (see Figure 6A; e.g. KUFFNER et al., 2008; SEMESI et al., 2009; NOISETTE et al., 2013; JOHNSON et al., 2014), but also in photosynthesis (e.g. ANTHONY et al., 2008; JOHNSON; CARPENTER, 2012; COMEAU et al., 2012; JOHNSON et al., 2014; KATO et al., 2014; TAIT, 2014), cell wall thickness (RAGAZZOLA et al., 2012; MCCOY; RAGAZZOLA, 2014b), reproduction (CUMANI et al., 2010), recruitment (KUFFNER et al., 2008), and survivorship (DIAZ-PULIDO et al., 2012). These strong negative OA effects on coralline algae have been shown to alter the competitive interactions between different species of these coralline algae (MCCOY; PFISTER, 2014a), between coralline algae and non-calcified algae (JOKIEL et al., 2008; KUFFNER et al., 2008; PORZIO et al., 2011; HOFMANN et al., 2012; KROEKER et al., 2013a,b), and also between coralline algae and grazer (MCCOY; PFISTER, 2014a). PORZIO et al. (2011) demonstrated a loss of 25% of coralline algae diversity in environments that are naturally acidified by submerged vents of CO_2 off the Italian coast. These changes in the phytobenthic communities in acidified environments reinforce the hypothesis that different ecophysiological susceptibilities of different taxonomic groups will result in profound changes in the physiognomy of these benthic environments in the coming decades.

Most studies related to global climate change effects on coralline algae have focused so far on their response to OA, while only a few have also included other environmental factors (see Figure 6B), such as temperature (e.g. JOHNSON; CARPENTER, 2012; MARTIN et al., 2013; NOISETTE et al., 2013; COMEAU et al., 2014) and light conditions (GAO; ZHENG, 2010; COMEAU et al., 2014), or local factors, such as nutrient concentration (RUSSELL et al., 2009; STENGEL et al., 2014).

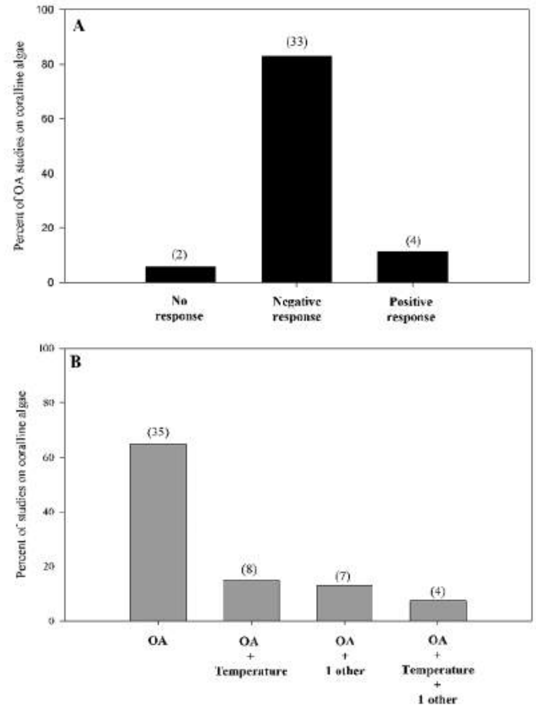

Figure 6. (A) Type of response of coralline algae (growth/calcification) reported in ocean acidification studies (n = 31), and (B) classification of experimental marine climate change studies on coralline algae (n = 56 studies) according to the climate variable tested (OA- ocean acidification, Temp.-temperature)

Besides a variety of studies investigating the OA response in coralline algae, only a few studies have been performed on the effect of the increase in seawater temperature and possible synergistic effects of ocean warming and acidification (see Figure 6B).

Generally, ocean warming is expected to affect algal community structure, seeing that temperature is an important general driver of the algal life cycle and consequently, of their phenology and distribution (RICHARDSON, 2008). All these changes can have a decisive impact on the changes in the distribution of populations, expanding the edges of the tropical population to higher latitudes, or excluding populations of colder waters (low temperature dependent) from their current subtropical or warm temperate environments, pushing them beyond these edges.

Studies combining OA and ocean warming scenarios have shown that there can be synergistic effects between both factors. For example, in *Porolithon onkodes*, the increase in CO_2 causes high mortality and necrosis only when under high temperatures (>28°C, DIAZ-PULIDO et al., 2012). In other experiments with the encrusting alga *Lithophyllum cabiochiae* from the Mediterranean, an additive effect of temperature was observed, resulting in higher mortality, necrosis and dissolution of the calcareous skeleton at high temperatures (MARTIN; GATTUSO, 2009). Thus both seawater pH and temperature, whether alone or in combination, will most likely change the physiognomy of rhodolith beds in the near future (see Figure7).

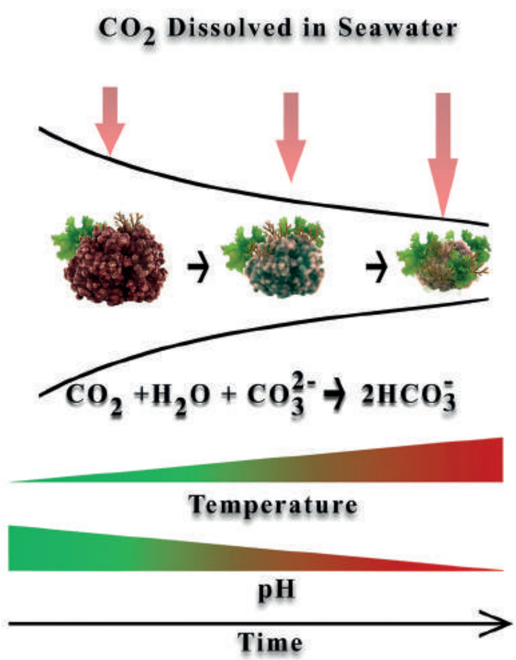

Figure 7. Schematic representation of rhodolith bed physiognomy impacted by warmer and more acidified waters in the future oceans, as predicted by the IPPC (2014).

Much of the effort that has addressed the impacts of climate change on the biology of marine primary producers remains limited and has dealt with aspects related to two initial treatment factors, acidification and temperature (WERNBERG et al., 2012). However, these factors have been occurring concomitantly, with other factors related to various processes associated with further changes in climate and other sources of stress. Thus, the significant future increase in rainfall (FAXNELD et al., 2010) as predicted to occur in south-central South America (IPCC, 2014) should act in parallel to the first two factors, changing environmental conditions, especially in coastal regions (see SCHERNER et al., 2012).

In addition to the future changes in temperature and the pH of seawater, there are other co-occurring drivers of environmental change, such as enhanced river run-off/sedimentation due to an increase in rainfall (IPCC, 2014). Thus, larger volumes of sediments will be transported to the continental shelf. Sedimentation can influence the survival and growth of rhodoliths. WILSON et al. (2004) showed that rhodoliths when buried under gravel suffered less severe effects than those buried under fine sediment. They related the differences between sedimentation effects to the movement of water around the thalli, which also restricts gas exchange. Mud-rich sediment with high concentrations of sulphide was quite harmful to rhodoliths and associated biota. Also, rhodolith beds can be affected indirectly by discharges of drill cuttings from oil and gas activities (DAVIES et al., 2007). These activities on the Brazilian shelf adjacent to the beds result in a fine sediment cover of the algae that can cause reductions in their net primary production up to 50-70% (RIUL et al., 2008; FIGUEIREDO et al., 2015). This reduction in primary production severely impacts rhodolith-forming algae, and has high potential to compromise the establishment of associated diversity.

A greater amount of rainfall increases the flux of nutrients from urban and rural environments into the ocean, fertilizing coastal areas (VIAROLI et al., 2005; FAXNELD et al., 2010). Moreover, the growth of the human population and the increasing use of coastal areas represent the main sources of nutrient enrichment in marine environments, especially from sewage discharges (HALPERN et al., 2008; TEICHBERG et al., 2010; LUO et al., 2012). An increase of sewage-derived nutrients in the coastal marine environment changes the structure of phytobenthic communities in urbanized areas (MARTINS et al., 2012, SCHERNER et al., 2012).

An increase in the concentrations of dissolved nutrients in rhodolith beds constitutes an extremely important threat to this ecosystem (WILSON et al., 2004). Inorganic nitrogen and phosphate are the two most important nutrients for macroalgal growth and are consequently what promotes excessive blooms in macroalgal biomass (VIAROLI et al., 2005; TEICHBERG et al., 2010). Macroalgal blooms can produce conspicuous shifts in the marine benthic communities (SCHENER et al., 2012). Thus, nitrogen and phosphorus are considered limiting nutrients in many marine ecosystems (ZEHR; KUDELA, 2011). Opportunistic species, such as *Ulva* spp., are highly favoured in terms of growth with increasing quantities of nitrogen in the form of nitrate and ammonium (LUO et al., 2012). RUSSELL et al. (2009) observed that filamentous turfs are highly favoured by the increase in nutrients. On the other hand, perennial species, such as *Sargassum stenophyllum*, are negatively affected by increases in nutrient concentration, as evidenced by a decrease in photosynthesis with increasing concentrations of ammonium (SCHERNER et al., 2012). However, in the same study, in *Ulva lactuca*, the increase in ammonium concentrations produced an increase in photosynthetic activity. Thus, nitrogen pollution affects algae differently, depending on the species and eventual interaction with other factors (MARTINS et al., 2012). GRALL and HALL-SPENCER (2003) have described the effects of agricultural pollution, urban sewage, and industrial waste on rhodolith beds in France. The main consequences were similar to those described for other types of sedimentary habitats and environments, such as an increase in siltation and a higher abundance and biomass of opportunistic species, which replace sensitive ones. A radical change in rhodolith-associated biota together with a reduction in species diversity and area of live rhodolith cover was observed. The authors mentioned two rhodolith beds that have been killed in the Bay of Brest, both of which were situated directly under sewage outflows.

Of all the factors that determine the structure of a rhodolith bed, the regime of waves and currents is the most significant (ATABAY, 1998). Rhodolith beds require high energy hydrodynamic regimes. The fragmentation of coralline algae deposits culminates with the formation of new individuals, storms being the main driving force for the formation of rhodolith beds. However, rhodolith beds do not develop if the water dynamic is excessively strong to the point where it causes unsustainable loss rates of thalli, or transports individuals outside suitable habitats. Likewise, weak currents and wave action cause stabilization and overgrowth by larger algal species or burial by fine sediments, leading to rhodolith death (MARRACK, 1999; FOSTER et al., 2013). Although poorly documented (FREIWALD, 1995), these phenomena are keys to understanding the structure of the rhodolith bed community and its dynamics. Water transparency is also a fundamental factor in the distribution of rhodolith beds (CANALS; BALLESTEROS, 1996).

As documented by AMADO-FILHO et al. (2010), the diversity and abundance of the associated community of a shallow-water rhodolith bed is inversely related to the frequency and intensity of extreme events or cold fronts, which are more frequent and intense especially during the winter (PASCELLI et al., 2013). These phenomena may increase water motion and the frequency of the rolling of rhodoliths, eroding the surface and reducing the diversity and biomass of associated soft-bodied algae. It should also be borne in mind that these phenomena reduce light availability near the bottom, theoretically reducing the potential primary production of these formations.

Interactions between global and local stressors

Besides the anthropogenic impacts that increase nutrient concentrations in coastal regions (MARTINS et al., 2012), global-change related scenarios that predict more intense and frequent rainfall will also result in more river run-off. Hence, larger volumes of land-derived pollutants will be transported to the continental shelf, severely impacting coastal marine communities. This drainage can reduce the pH and enhance the CO_2 concentration even further, especially in anthropogenically influenced estuaries, aggravating the global impacts (NORIEGA et al., 2012). Thus, drainage basins and associated estuaries represent important regions for evaluating interactions between local and global stressors (HOWARTH et al., 1995; CANALS; BALLESTEROS, 1996), including variations in rainfall patterns.

There are different ways in which global factors, such as temperature and acidification, can interact with local factors, such as nutrients: (1) isolated: the effect of each factor is not influenced by the effects produced by other factors studied independently; (2) additive: factors have a joint effect on the study object that is equal to the sum of the effects caused by each factor when tested in isolation; (3) synergy: the factors have a joint effect on the study object that is greater than the simple sum of the effects caused by each factor when acting in isolation; and (4) antagonistic: the factors have a negative interaction, one neutralizing the other. Most studies have focused on one factor at a time, few have addressed two factors simultaneously and rarely have three or more been tested together to assess the existence of potential multiple levels of interaction (Figure 6). It is true that experimental designs with three or more factors are difficult to implement because the number of necessary replicates increases exponentially and interpretation of results can become too complex. An example of a synergistic interaction has been given by RUSSELL et al. (2009), who detected an interaction between the effects of high pCO_2 and nutrients on photosynthesis and algal cover parameters, compromising the performance of calcareous algae and encouraging the growth of turf species. Thus, local stressors, as well as climate change factors - have to be considered in the evaluation of likely future scenarios.

Considerations for future research

Although important and abundant throughout the Brazilian coast, rhodolith beds are still poorly understood in many aspects. For example, recent molecular results (SISSINI et al., 2014; VIEIRA-PINTO et al., 2014) have reinforced the need for molecular information to clarify taxonomy and distribution patterns of key rhodolith bed-forming species. This is important in the context of conservation strategies, as without basic information about the distribution of the genetic diversity and population genetic connectivity of keystone, foundation and main engineering marine species along the Brazilian coast, conservation and management strategies may be compromised.

Another aspect that needs attention is the threats that global change and its possible interactions with local stressors represents for rhodolith beds. These threats can have numerous consequences for these ecosystems but, unfortunately, in Brazil studies investigating the impact of global change and/or local stressors are still lacking (KERR et al., 2016).

This demands networking within the Brazilian scientific community, in order to coordinate, for example, collective efforts to perform baseline characterization of these formations in Brazil. This characterization on a large scale will provide us with a better understanding of the factors that determine different patterns of diversity and abundance. This pioneering survey will also allow the selection of key areas for the implementation of a program for long-term monitoring. It will provide us with vital information for the creation and improvement of models that will enhance our ability to predict the distribution of these beds and their associated fauna and flora in the coming decades.

In order to provide evidence of the expected consequences of global change and possible interaction with local stressors for the marine environment, within a reasonable timeline (i.e. 5-10 years), we also need to prioritize where research efforts have to be placed. The three topics agreed upon by the authors, which should be given greatest priority are: (1) understanding how OA will interact with other anthropogenic and climatic stressors, (2) understanding whether species may adapt or become acclimatized to future OA conditions and how this will affect species interactions and ecosystem stability, and (3) monitoring and modelling temporal, spatial and habitat variability in carbonate chemistry in order to more accurately predict future changes on the regional and local scale. Whilst these topics are seen as particular priorities, in answering questions regarding the expected consequences of OA, many of the topics we have listed are interlinked, providing the background and context for other research areas. This represents a difficult task, requiring multi-stressor experiments with complex experimental designs that will require increased collaboration and joint funding initiatives to allow the manpower, expertise and funding to successfully carry them out. This will be vital, if we are to develop the most appropriate strategies for the mitigation or remediation of or even the adaptation to future scenarios related to global climate change.

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Marine and coastal environmental education in the context of global climate changes - synthesis and subsidies for ReBentos (Coastal Benthic Habitats Monitoring Network)

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Abstract

As changes in coastal and marine environments are expected to negatively affect Brazilian ecosystems, the importance of Marine Environmental Education (MEE) comes to the fore. However, so far only 32 contributions related to this issue have been published in Brazil. The MEE workgroup of ReBentos aims at promoting EE and the communication of marine ecological research to the scholastic public as a whole, as well as to groups which exert an influence on general perception, such as the media, politicians, and scientists. This paper presents an overview of the initiatives of MEE in Brazil, with emphasis on the ReBentos projects and guidelines. The conceptual background of action is based on the Rio'92 Treaty on Environmental Education, thereby implying an MEE with Transdisciplinar, emancipatory and reflexive characteristics, directed to changes in values, principles and attitudes. During the period 2011 to 2015, 10 projects were developed from Alagoas to Santa Catarina States, involving the development, implementation and testing through scientific research of 16 MEE activity-models. The didactic material subsequently produced comprised three books and 21 book-chapters. A public of around 6,500 Conservation Unit visitors, 250 public school teachers and 800 high school students have been impacted to date. To act as monitors and multipliers, 250 undergraduate students and professionals were trained. Research project evaluation generated the publication of nine papers. As a further step, the need for protocol elaboration for each model is placed in evidence, in order to direct and facilitate future initiatives.

Descriptors: Marine environmental education, Climate changes, Marine biodiversity, Long-term monitoring.

Resumo

A importância da educação ambiental marinha (EAM) vem tomando relevância à medida que aumenta a expectativa de impactos nos ecossistemas brasileiros ocasionados por mudanças nos ambientes costeiros. Entretanto, apenas 32 contribuições sobre esse assunto foram publicadas no Brasil. O grupo de trabalho em EAM da ReBentos objetiva promover a comunicação da pesquisa ecológica marinha para o público escolar como um todo, bem como a grupos com influência na percepção comum, como a mídia, políticos e cientistas. Este trabalho apresenta uma visão das iniciativas em EAM no Brasil, com ênfase nos projetos e diretrizes da ReBentos. A base conceitual de ação é o Tratado de Educação Ambiental da Rio 92, implicando em um ensino com características transdisciplinares, reflexivas e emancipatórias, dirigidas a mudanças em valores, princípios e atitudes. Durante o período de 2011 a 2015, 10 modelos de atividade foram desenvolvidos, de Alagoas a Santa Catarina, envolvendo sua concepção, implementação e teste por meio de pesquisa científica. O material didático produzido compreendeu três livros e 21 capítulos de livros. Um público total ao redor de 5500 visitantes de UCs, 250 professores de escolas públicas e 800 estudantes foi impactado. Como monitores e multiplicadores, foram treinados 250 estudantes de graduação e profissionais. Projetos de avaliação de pesquisa geraram nove trabalhos científicos. Como uma próxima iniciativa, é salientada a necessidade de elaboração de protocolos para cada modelo, a fim de direcionar e facilitar futuras iniciativas.

Descritores: Educação ambiental marinha, Mudanças climáticas, Biodiversidade marinha, Monitoramento de longo prazo.

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INTRODUCTION

Environmental education: state of the art in Brazilian marine and coastal ecosystems

Although marine ecosystems comprise extremely rich natural resources and a fantastic germplasm bank of organisms, both of which must be preserved at all costs, Brazilian Environmental Education has been practically restricted to terrestrial environments alone.

Both abroad and in Brazil, Marine Environmental Education (MEE) is very little cited in specialized scientific journals. In a synthesis about the literature on Marine Environmental Education in Brazil (MEEB), PEDRINI (2010) selected 32 published contributions which represented the entire national literature. He also presented a typology with six types of MEEB approaches: a) by socio-environmental actors, viz., students in an elementary school near Fernando de Noronha National Marine Park (SILVA JR. et al., 2010); b) by ecosystems, such as urban mangroves within Florianópolis city (Santa Catarina State) (PANITZ, 2010); c) by iconic, flagship or charismatic species, such as dolphins along the Rio de Janeiro State coast (GURGEL et al., 2002); d) by aquariums and oceanariums, such as the Ubatuba Aquarium (Coast of São Paulo State) (GALLO NETO; BARBOSA, 2010); e) by marine biology classes, mainly as free courses directed to elementary or high school students; and f) by virtual environments (GUERRA, 2002).

It is also possible to find research on the evaluation of negative ecological impacts caused by divers, tourists and vessels in marine and coastal environments (CREED; AMADO FILHO, 1999; GHILARDI-LOPES et al., 2015; HAWKINS; ROBERTS, 1993; HAWKINS et al., 1999; PEDRINI et al., 2007; PLATHONG et al., 2000; ROUPHAEL; INGLIS, 2001; SILVA; SILVA JR., 2002; SILVA et al., 2012a; SILVA; GHILARDI-LOPES, 2012; TUNALA et al., 2013), as well as that regarding the efficiency of MEE from an educational perspective, and on the reduction of these impacts (BARKER; ROBERTS, 2004; BERCHEZ et al., 2005; CORREIA; SOVIERZOSKI, 2009; 2010; KATON et al., 2013; LUNA et al., 2009; MEDIO et al., 1997; PEDRINI, 2010; PEDRINI et al., 2008; SALM, 1985; TOWATA et al., 2013; TOWSEND, 2000; URSI et al., 2013; WALTERS; SAMWAYS, 2001; WORACHANANANTA et al., 2008).

EE activities that contemplated marine ecosystems and that have already been developed in Brazil, although equally rare (BERCHEZ et al., 2005; PEDRINI, 2010; WEGNER et al., 2006), were extremely important for the development of a mindset for their conservation. Although with a poorly defined conceptual and methodological structure, and basically involving the simple observation of local ecosystems together with technical learning, activities enthusiastically carried out since the 80's by diving schools can be cited as an example, through the consequential and substantial reduction in sport submarine-fishing, and the increase of the spirit for conserving these environments and their organisms.

Examples of conservation activities with well-defined objectives and structures include that of marine chelonians (Tamar/IBAMA Project), marine mammals along the Rio de Janeiro State coast (GURGEL et al., 2002), the northeastern Brazil marine reefs (OLIVEIRA; CORREIA, 2013b; SILVA et al., 2013b), the Abrolhos Marine Park, (MELO et al., 2005) and, finally, southeastern Brazil rocky-coasts (BERCHEZ et al., 2007; PEDRINI et al., 2011). In São Paulo State, and within the Subaquatic Trail Project (BERCHEZ et al., 2007; GHILARDI; BERCHEZ, 2010; URSI et al., 2010; URSI et al., 2009), environmental education-activities models based on interpretative trails, have been developed, applied and afterwards tested through specific research projects.

Other conservation activities can be indirectly related to EE, as is the case of the Alcatrazes Project, mainly dedicated to protection of the Archipelago of the same name (São Paulo State), whose ecosystems are threatened through target practice by the Brazilian Navy (CAMPOS, 2008).

MEE activities related to marine trails are cited by WEGNER et al. (2006) on the northern coast of Santa Catarina State, BERCHEZ et al. (2007) on Anchieta Island rocky shores, HADEL and BERCHEZ (2005) within the CEBIMar-USP monitored visitation Program at Segredo Beach (São Sebastião, São Paulo State), and PEDRINI et al. (2011) with the Ecoturismar Project in Rio de Janeiro State.

Most of the accumulated experience has neither been published in specialized journals, nor have the results been scientifically tested. The little data available has been reported in the form of these or other means of publication, with only limited scope of disclosure.

Due, among other factors, to the lack of data, it is possible to observe differences in the structural patterns of MEE activities, both between those which are well-informed and planned, and those which are only empirical and inconstant in time. In many cases their potential is underrated, due to conceptual and operational mistakes. In other cases, attempts have even resulted in negative action, with immediate negative impacts on nature, and the possible assimilation of behaviors contrary to those desired. The opening of protected areas to exorbitant, irresponsible, impacting and excessively commercial tourism can be cited as an example (REUSS-STRENGEL et al., 1997).

The creation of models with well-defined conceptual and philosophic bases and structures, and their testing by means of parallel scientific studies, is thus of great importance in the management of marine-protected areas, or even of areas which encompass coastal and marine environments and organisms, and where the implementation of activities adapted to local conditions should be encouraged.

Environmental education in the context of climate changes

The Intergovernmental Panel on Climate Change (IPCC) reports that global changes, besides occurring at a faster rate than at any other period in time over the last 25 million years, are already causing innumerable impacts in marine environments (BELLARD et al., 2012; IPCC, 2014). Nowadays, there is a consensus among scientists as to anthropogenic influence on global climate changes (DORAN; ZIMMERMAN, 2009). Furthermore, ROCKSTROM et al. (2009) also pointed out climate changes as being one of the planetary boundaries that have already been crossed by human activities, thereby possibly leading to “the risk of irreversible and abrupt environmental changes”.

The expected changes in coastal and marine environments, such as the average rise in sea levels, changes in both local and global marine currents, and rises in temperatures and seawater-acidification (BERCHEZ et al., 2008), can negatively affect many Latin American ecosystems (TURRA et al., 2013), many of which, besides being unique, constitute biodiversity hotspots (MILOSLAVICH et al., 2011), such as the kelp forests in the Cape Horn Biosphere Reserve (ROZZI et al., 2012), the extensive rhodolith beds in the Southwest Tropical Atlantic (BERCHEZ et al., 2009), and the highly biodiverse coral reefs of the Tropical Atlantic, with their high number of endemic species (CORREIA; SOVIERZOSKI, 2012; LEÃO et al., 2003). Thus, not only is concern for the protection of these environments essential, but also critical discussion capable of presenting the complexity of the problem, and improving changes in social structure.

Although the effects of climate change on coastal and marine environments can be expected, and in a certain way, understood, in scientific and academic environments, a large part of the population is not only ignorant of or has no access to this information, but knows absolutely nothing about these ecosystems and their intrinsic value. Since any posture-change in relation to the environment, which is directed towards minimizing and possibly reverting the anthropogenic influence on global-climate changes, is not only a government responsibility, but also of concern to each citizen, we are facing a great challenge, for there is clear detachment between comprehension of climate change phenomena and everybody’s ‘day-to-day’ existence (TAMAIO, 2010; 2013). As an example, few people are conscious that fundamental economic activities, such as fisheries and coastal and marine ecotourism, depend on the quality of marine environments, and that any alteration thereof will have a consequential and detrimental impact. New research has demonstrated that people generally overestimate how common their own opinion is, and in doing so, they are less likely to change their views on climate changes (LEVISTON et al., 2013).

Perception that long-term climate trends are related to human causes has been shown to be dependent on scientific consensus (LEWANDOWSKY et al., 2013). Moreover, political group consensus on anthropogenic global warming has proved to be a primary factor in social-perception (BRECHIN, 2012). Without this, even scientific agreement on climate change may have a limited impact.

In this context, Environmental Education (EE) figures as the base for accomplishing a transformative and critical approach to the theme, thereby making it possible, in the near future, to amplify mobilization efforts and intensify civil-society action, in such a way as to alert world leaders on their role in guiding this emergent challenge. It is clear that, besides the general and scholastic public, EE focusing on the media, politicians, and even scientists themselves, would clarify the importance of these groups in overall public perception.

Environmental education is conceivably a permanent educational activity, through which the community becomes conscious of both reality and the novel relationships that mankind has established with nature, and consequently, of the problems derived from this relationship and their profound causes. From this awareness, attitudes and values that could capacitate a surpassing transformation of this same reality are possible (GONZÁLEZ GAUDIANO, 2005) (Figures 1 and 2).

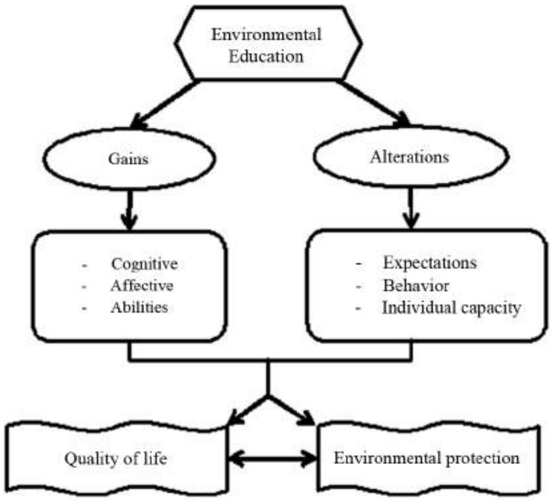

Figure 1. Holistic environmental education.

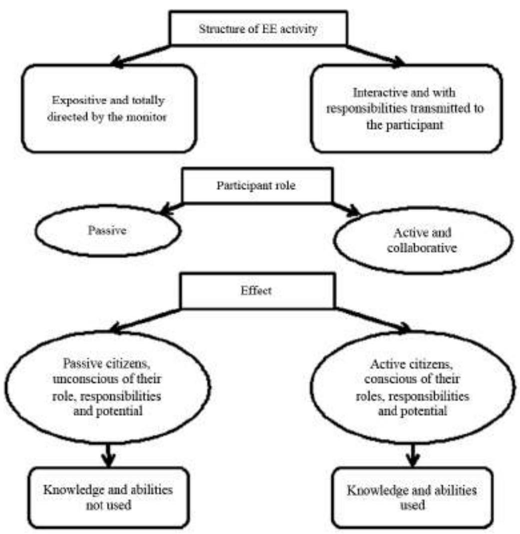

Figure 2. Expected effects of the different approaches of environmental education activities.

These concepts, drawn from pedagogic assumptions and embodied in the *Tbilisi Declaration on Environmental Education,* and also expressed in the Rio-92 *Treaty on Environmental Education for Sustainable Societies and Global Responsibility* (PEDRINI; BRITO, 2006), have been adopted by the Brazilian National Environmental Education Program (BRASIL, 2005). Table 1 shows some of the conceptual indicators of the treaty (BERCHEZ et al., 2007), which, in spite of the inherent premise fundamentality and favorable credibility sustaining further MEE action, have not been considered in numerous projects.

PEDRINI and SABA (2008) report a new approach to the global environmental changes (GECs) theme. It employs the movie "An inconvenient truth" (produced by Al Gore to make the issue of global warming a recognized problem worldwide), as a strategy for teaching English among public high school students.

Table 1. Short description of some conceptual EE indicators.

Indicator (EE)	Indicator description
Transforming	Facilitates changes in attitudes for the development of sustainable societies.
Participative	Encourages participation in collective mobilization
Embracing	Involves all the various social groups
Permanent	Performed as a continuous activity (or continued EE)
Contextualized	Acts directly on the reality of the activity and on achieving global dimensions
Ethical	Respect for human beings and all life-forms
Interdisciplinary	Integrates various forms of knowledge
Holistic	Aims at transforming the individual, e.g. values and ethical concepts
Multiplying	Aims at expanding activities through the formation of multipliers

Although there are some EE initiatives related to climate changes in Brazil, a clearer relationship between day-to-day actions, their synergies (e.g. locomotion, over-consumption, housing, feeding, land-use, deforestation, river-silting, desert-formation) and the increase in greenhouse-gas emission (TAMAIO, 2010; 2013), is still necessary. EE programs and actions should also be conceived in an accessible language, compatible with the different publics, for effective population-awareness of the causes and impacts due to climate change (MONZONI, 2009), thereby promoting systemic comprehension, and holistic and contextualized thinking about the complexity of the problem.

METHODS

Initial rebentos guidelines for marine environmental education

The aims of the MEE workgroup of the Coastal Benthic Habitats ReBentos Monitoring Network (MCT/ CNPq/ MEC/ CAPES/ FNDCT – Ação Transversal/FAPs, FAPESP process nº 10/52323-0), is to incite environmental education and scientific communication of marine ecological research to the public, as a whole. An initial protocol, based on conceptual issues, as well as the previous experience of the participants, was proposed to serve as a general basis for MEE workgroup projects.

Conceptual issues should be based on the Rio-92 *Treaty on Environmental Education for Sustainable Societies and Global Responsibility*, which serves as a base for Brazilian EE legislation (Law n° 9.795, April, 1999) and the National EE Program (ProNEA). This implies a holistic vision of EE, mainly directed to changes in values, principles and attitudes (LA TROBE; ACOTT, 2000) of a multi, trans-discipline emancipatory and reflexive character, capable of facilitating movement towards individual emancipation and more sustainable societies. This vision is not antagonist, but encompasses that which visualizes EE as a form of biological, ecological or social education. Artistic, physical and philosophic disciplines, among others, become instruments and fall under the EE wing.

Public – The main goals of ReBentos EE action and materials are to reach opinion and policy-makers, with the aim of maximizing and spreading efforts. Once again, this is not antagonist, but complementary to more conventional approaches, such as those that deal with elementary and high school students, or local communities.

Lines of action – Based on preliminary ReBentos experience, the EE-ReBentos projects should be related to (1) the production of educational material, (2) the development of environmental educational models, (3) education evaluation, and (4) long-term evaluation of the perception of basic GEC concepts, and their consequential effects.

On incorporating the question of marine GECs, education material and methods would acquire a direct approach towards cognitive gains, with the application of indirect strategies directed to affective gains or the development of specific skills. In the latter case, the conceptual relationship with GECs would be clearly shown, both in the project, and to those that will make use of the resource. Explicit reference to ReBentos should appear in the products and projects, and during EE activities and staff-training courses.

RESULTS

Projects, actions and results from 2011 to 2015

1. Subaquatic Trail

Coordinator: Flávio Berchez, IB-USP

Objectives

The Subaquatic Trail Project was begun in 2001 in Anchieta Island State Park (Ubatuba City, São Paulo State, Brazil), with the proposal of an innovative environmental education approach towards marine environments, based on the creation, implementation and scientific evaluation (both educational and ecological) of models.

Description and Conceptual background:

The general structure, common to all models, is based on guided interpretative trails (COSTA; COSTA, 2000), in which the participants stop at pre-defined spots, where certain issues are discussed with the monitor(s). Each spot corresponds to a stage in an activity with specific educational objectives involving a holist relationship with the marine environment.

Although greater emphasis is given to the rocky-shore ecosystem, since this is the team's main focus, other models have been developed in other coastal environments. The models have been applied mainly in the counties of Ubatuba and São Sebastião, São Paulo State.

Model-structuring was based on the holistic environmental education concept (Figure 1) adopted by the Brazilian National Environmental Education Program (BRASIL, 2005). The aim is individual transformation and evolution, along with an understanding of natural phenomena in an integral way (WEIL, 1991), thereby leading to behavioral, ethical and value changes acquired through cognitive, skill and emotional gains related to the ecosystems visited (HEIMLICH, 2002).

Apart from model-elaboration, the main aim is to prepare college educators, capable of spreading information and concepts. Operational structure involves not only the activities themselves, but also mainstays, such as personal training and security. The evaluation of both educational outcome, based on EE research techniques, and the negative ecological impacts of the activities within the environment, is complementary.

Furthermore, the activities present a multidisciplinary approach to interpretation of the environment (Table 2), through relating the functional aspects of ecosystems with biotic and abiotic factors, and organism adaptation, as well as furthering discussion of conservation and the main anthropogenic impacts on marine and coastal environments. As regards diving, integration is centered on specific diving equipment techniques and performance, and on the action of factors, such as water temperature and human-body pressure, on anatomy, physiology, physical conditioning and health.

Activities are always carried out in groups, with the number of participants per model varying in accordance to security and conservational aspects. Interaction among the elements of the group is incited by the monitor, through quizzes and educational activities aimed at stimulating participative behavior (Table 1 and Figure 2).

Preliminary Results

Protocol - Creation of standard procedures, including (1) chronological teaching sequence, (2) minimum-knowledge base that models should encompass, and (3) intended cognitive, affective and ability gains, and the didactic posture needed for their achievement. So far, eight models have complied: underwater trail outside the water, free diving trail, SCUBA diving trail, natural aquarium trail, ecosystem trail, vertical trail, kayak trail, lectures about marine ecosystems.

Didactic material support - books (BERCHEZ et al., under preparation; GHILARDI-LOPES et al., 2012; MARQUES; PEREIRA FILHO, 2013), websites (sites–www.ib.usp.br/ecosteiros2 – and distance education tools (video-classes based on the Moodle Platform).

Monitor training and formation – 250 environmental monitors have been prepared to apply the protocol, this comprising students, professionals in the areas of biology, oceanography, geology and education, protected area technicians and managers from several states of the Brazilian southeastern, southern and eastern regions. The training consisted of participation as extension or undergraduate Univ. of São Paulo students (BIB-0529 - Teoria e prática de educação ambiental em UCs marinhas) in (1) a blended learning theoretical course, followed by one week of practical monitoring in one of the model activities.

Implementation of models – the models were applied to the general public visiting protected areas (7,805 visitors), to the recycling of public school teachers (24), and to correspondent students of technical (tourism) schools (110, 14 with visual or hearing deficiencies). In the case of teachers, special certified capability was related to the use of active diving, as a centralizing theme for promoting school-discipline transversal integration. Preparation was also extended to student monitoring.

Evaluation of activities – efficiency and change in perception as regards climate changes and the marine environment, was evaluated through research projects. Evaluation of the ecological impacts related to the absence of visiting protocols in the region of the natural aquarium trail, was through a master's degree monograph (SPELTA, 2011). This was extended to public perception of global climate changes, with emphasis on expected alterations to and impacts on the marine environment (GHILARDI-LOPES et al., 2013b; GHILARDI-LOPES et al., 2015). Following the extension of the concepts and models to Chile, a comprehensive review about integrated approaches between ecology and education in South America Marine Protected Areas was prepared (BERCHEZ et al., 2015).

2. Games about Climate Changes and their effects on Marine and Coastal Environments Project

Coordinator: Natalia Pirani Ghilardi-Lopes, UFABC)

Objective

The main aim of the project is to develop, apply and test two educational web-based games with elementary

Table 2. Main fields of knowledge presented during the activities of the Subaquatic Trail Project.

Field of knowledge	Discussed aspects
Biology, ecology and environment conservation	Most important or attractive organisms - nutrition, behavior and ecological and economic importance.
	Organism ecological interactions - predation, competition, epiphytes, succession.
	Community ecology - diversity and community structure;
	Conservation and protection of marine ecosystems, rules of minimal impact.
	Rules, function and importance of marine protected areas (Brazilian conservation units).
	Global climate changes and their effects on marine and coastal ecosystems.
Chemistry and Physics	Salinity, nutrients, temperature, hydro-dynamism and radiation, and their importance for living beings.
	Pressure related to diving (embolism, narcosis, organic compression).
	Physics related to diving equipment.
Geology	Consolidated and unconsolidated substrates - kinds and origin.
	Erosion and weathering.
Physical Education and the human body	The importance of physical activities.
	The correct practice of physical activities - stretching and heating, free and SCUBA diving techniques.
	Physiology and anatomy of the human body in relation to diving;
	Body consciousness.

school students and their teachers, and also, to promote continuing education for teachers.

Description and Conceptual background

The idea of the project came from the easy access to information through technology, and from people nowadays being active agents of their own knowledge-construction process. When properly done, i.e. through reliable sources of information, this behavior can result in significant learning, in which the newly acquired information is anchored on relevant concepts already present in the cognitive structure of the apprentice, and on new concepts constructed in an interconnected way and with a real meaning (AUSUBEL et al., 1980). In accordance with this tendency, the use of communication and information technologies is more and more encouraged and prompted in formal educational systems (DEANEY et al., 2003; LIM et al., 2005).

In this context, educational games of free access in the web, or available for restricted classroom use, when adapted to the general public, can serve as powerful tools in the process of disseminating scientific information, and for facilitating its apprehension and comprehension, this beyond the direct and experiential interaction of the knowledgeable apprentice, thereby changing behavior and inciting active participation, with the consequential improvements in socio-environmental quality, (Table 1, Figures 1 and 2).

When playing, a person simulates and creates realities, within certain mutually accepted rules, roles, conditions and premises, thence taking the place of somebody else, and so developing an understanding of why people act in certain ways. Thus, the players learn how to act and make mistakes, without negative consequences to the real world, since certain realities can be simulated, played out, manipulated and experimented, and the possible consequences felt. If these are negative, things that should not be done are learned, thereby making it possible to plan alternative approaches or objectives. The players can also share their experiences, develop their collaborative spirit, and use the game for self-knowledge, thence understanding their own attitudes, values and thinking processes better, as well as comprehending and feeling their very limitations and possibilities of promoting changes. Moreover, games, besides generally being fun and pleasurable, afford a way of intensifying the emotional bond between the player and the subject of the game.

Systemic games comprise a category specifically aimed at showing the players how complex systems function. These games are extremely interesting in the context of global climate changes that result from of the interaction of diverse components of ecological systems. Systemic games facilitate seeing, feeling and experimenting several aspects of the system's behavior that are important in the transformation of reality and in the context of "feeling part of a larger picture". The player, although able to influence the system, cannot always direct it in a desirable way, which means that attempts must be made to understand the way things work and find other ways of promoting the required changes, such as identifying the crucial points involved in its functioning (DIELEMAN; HUISINGH, 2006).

Preliminary results

The two games developed in the project were:

Game-book "Challenge in Apicum" (GHILARDI-LOPES, 2014) – based on RPG (Role Playing Games) solo adventures, in which the participant will play the role of a student, who must discover the causes of the changes that are occurring in the surroundings of Apicum City (a fictional coastal city specially created for the game). For this, the participant will have to carry out quizzes, puzzles and activities (GHILARDI-LOPES et al., 2013a; SILVA et al., 2013a). The game is under test. It was applied to 135 elementary school children, who filled in questionnaires before and after playing, which are being analyzed. The game-book can be accessed at the following link: http://professor.ufabc.edu.br/~natalia.lopes/jogosmarinhos/index.php/material-de-apoio-2/16-livro-jogo

"Apicum" game – this game basically presents the same story as the gamebook, but in a more interactive interface. The educative game was developed in GameMaker® software. One important step in its development was to produce the Game Design Document (GDD), which includes a description of the story, objectives, rules, and all the characters and items of the game, as well as the Level Design Document (LDD), which includes a description of the scenarios, levels of the game (Table 3), the conditions of entrance and exit of each level, and the flow conditions at each level (what the main character can and cannot do). Both documents for the game are already finished, and the game is now being tested. It can be accessed at the following link: http://professor.ufabc.edu.br/~natalia.lopes/jogosmarinhos/index.php/prototipos-2. A page on facebook has also been developed (https://www.facebook.com/apicumgame). Subsequently, it will be applied to elementary and high school students, and evaluated in terms of educational efficiency.

Another result of the project was the Extension course for elementary and high-school teachers recycling (GHILARDI-LOPES et al., 2014a). Many teachers say they feel uncomfortable when addressing the subject of global environmental changes in their classrooms, since they know little about it. Taking this into account, an extension course on global changes and their effects on marine and coastal environments was given to 15 elementary and high school teachers. During the course, they prepared and applied a didactic sequence. At the end, they presented and discussed the results. All didactic sequences, as well as theoretical information on the subject of the course can be accessed at the following link (GHILARDI-LOPES et al., 2014b): http://professor.ufabc.edu.br/~natalia.lopes/jogos-marinhos/index.php/material-de-apoio-2/17-e-book.

3. Learning with the Sea Project

Coordinators: Benjamim Teixeira, Laura Pioli Kremer and Renata Costella Acauan, IFSC

Objectives

The main goal is to stimulate the introduction of marine knowledge into school activities, thereby contributing to the implementation of marine-environmental education activities in elementary and high schools.

Description and Conceptual Background

The project "Learning with the Sea" was initiated in mid 2012 in Santa Catarina State, and is under way. Santa Catarina, with a long coastline (531 kilometers), has an appreciable population closely related to the marine environment. However, knowledge of marine ecosystems is slight, and subjects related with this environment are rarely present in school activities. One way to develop marine-environmental education is to stimulate the introduction and integration of this theme into the school curriculum. With this in mind, and by using the marine environment as a starting point to teach the concepts of various subjects across the curriculum, the project comprises a means of developing marine-environmental awareness, and generating the understanding of marine processes, and how they are linked to local problems.

Project execution is through workshops for students and teachers, the latter as prospective multipliers, and procedures according to conceptual EE indicators (Table 1), with the constant stimulation of interdisciplinary dialogues between marine knowledge and daily school activities. The educational objectives of specific-workshop content are related with and linked to school curriculum disciplines. The basic knowledge content deals with marine biology, oceanography, human culture linked to the sea, the value of marine processes and resources, and global anthropogenic impacts on the marine environment.

Table 3. Levels of the educational game on global climate changes and their effects on marine and coastal ecosystems, with the objectives proposed for each one.

Level	Objective(s)
Introduction	Help people who have passed through a heavy storm Talk with marine ecologists
School	Learn about marine ecosystems and global climate changes
Individuals' homes	Make their homes more sustainable against greenhouse-gas emissions
Coral reef	Visit a coral reef, and measure environmental variables in order to understand why the corals are bleached
Store	Purchase diving equipment
Library	Learn about the issues dealt with in the game
University	Talk with a marine researcher and obtain help to understand the problems with the coral reef
Laboratory	Learn about equipment to measure environmental variables
City Hall	Choose a candidate to take care of the three dimensions of sustainability

Preliminary results

Implementation of models: with the participation of 1.253 students, 74 teachers and 20 monitors.

Evaluation of activities: the results were presented in three scientific events (ACAUAN et al., 2014; ACAUAN et al., 2012; KREMER et al., 2013).

Based on this project, a postgraduate course on Marine Sciences, as applied to Teaching (Ciências Marinhas Aplicadas ao Ensino) was created. This is an interdisciplinary course with 400 hours, which was initiated in 2014 at the 'Instituto Federal de Santa Catarina' Campus at Itajaí. Until now 35 students have participated. It is designed for pre-school, elementary and high school teachers from several fields of knowledge, such as science, social studies, languages and arts. The main goals are:

Facilitate the application of marine-science insights to learning environments.

Enhance students' knowledge of marine environmental sciences.

Integrate marine environmental learning within all the subjects at the pre-, elementary and high school levels.

Stimulate new possibilities of interdisciplinary knowledge-construction in schools.

Support educators by facilitating learning experience in the marine environment outside the classroom.

Provide students with opportunities to experience and investigate teaching practice.

4. Marvelous Brazilian Mangroves Program

Coordinators: Renato de Almeida, UFRB; Clemente Coelho Junior, UPE; Yara Schaeffer-Novelli, USP

Objectives

Support formal education programs in marine protected areas. The specific objective is to provide an educational tool to help teachers and community members to interpret coastal and estuarine systems. In this way, the 'Marvelous Mangroves' contributes towards implementing a National Communication Strategy and environmental education in protected areas.

Description and Conceptual background

'Marvelous Mangroves' is a curriculum guide that is formally introduced and presented to elementary school teachers (ALMEIDA et al., 2008). During the 16–hour-course, teachers are instructed on classroom and field use. The proposals for practical activities in coastal zone and marine ecosystems involve aspects of climate-change in the context of science and environmental education. After classroom activities, teachers are encouraged to develop projects covering an eight to ten month period. As these activities occupy about 84 hours, the duration of the whole course comes to 100 hours. Participants receive their certificates on termination. A system of training and evaluation, with the use of forms for teachers and students alike, facilitates monthly monitoring of all the teachers and schools involved. This strategy eliminates the punctual approach, common in educational projects. In Brazil, this program is coordinated by the Instituto Bioma Brasil (IBB), associated to the Mangrove Action Project (MAP), a US Non-Governmental Organization. To date, the Marvelous Mangrove curriculum guide has been applied in the towns of Cariacica and Fundão (Espírito Santo State), Maragojipe (Bahia State), Porto de Pedras (Alagoas State), and Tamandaré (Pernambuco State).

Preliminary Results

Records from circumstantial experience with curriculum guides in Brazil has shown that, besides reproducing the proposed exercises, teachers also used these guides for motivating activities not dealt with therein. Non-course-participants were also involved with the projects developed in their own schools.

Incentives by the Brazilian Ministry of Environment (MMA) for the use of the curriculum guide in interpretative programs in protected marine and coastal areas. Models were implemented in Cariacica (48 teachers, 19 schools), Fundão (61 teachers, 11 schools), Maragojipe (69 teachers, 14 schools), Porto de Pedras (30 teachers, 11 schools), and Tamandaré (30 teachers, 12 schools).

Dissemination of the curriculum guide in Brazil with support from MMA, local councils and other partner organizations. The Ministry of Education (MEC) also gave support to an extension project of the Federal University of Bahia Recôncavo (UFRB).

Human-resource training and studies presented in domestic scientific events (ALMEIDA et al., 2010; SILVA et al., 2012b).

Evaluation system strengthening and recognizing the potential, as well as educational and administrative limitations. Noteworthy is the participation of students and teachers in a discussion forum and Educators Collective, besides the production of a video and interactive blog.

5. Investing in new talent from the public education network for social inclusion and development of scientific culture

Coordinators: Monica Dorigo Correia and Hilda Helena Sovierzoski, UFAL

Objectives

Develop and improve the scientific and technological culture of teachers and students alike, in elementary and high schools of the Alagoas State public network, by conducting educational activities in the natural sciences area, aimed at encouraging the construction of new academic activities and teaching activities from a contextualized theoretical and experimental viewpoint, in order to awaken and broaden the vision of natural and scientific phenomena, as a strategy for the discovery of vocations and new talent.

Description and Conceptual background

This Project was begun in 2011, with three stages involving professors and students from public schools and undergraduate Biological Science courses, with grants from the Scientific Initiation Program (CAPES/UFAL). It also involved students from the Undergraduate Program of the Teaching of Science and Mathematics (PPGECIM/UFAL). All the students and both professors are associated with the Sector of Benthic Communities of the Federal University of Alagoas.

Information on biodiversity and the preservation of Alagoas coastal ecosystems is still little divulged in the media or presented in the state elementary and high schools. The need is known for expanding and improving human resources directed to increasing studies on biodiversity and the preservation of coastal ecosystems in the state of Alagoas, as well as the training of students and teachers in elementary schools. The methodology used in this context is based on three steps:

a) Development of experimental and pedagogical kits with the participation of basic education teachers, students of the Undergraduate Program in Science Education and Mathematics of UFAL (PPGECIM) and teacher-researchers of UFAL, thereby targeting the use of alternative educational and innovative material to be used in activities in stages 2 and 3 in this sub-project. In the future, these will be made available for use by other teachers in basic education.

b) Education courses and the updating of teachers in the area of Natural Sciences from the public basic-education network, in order to improve the teaching-learning process.

c) Implementation of the program "Saturdays at the Plant Science" consisting of regular visits by public school students and teachers, thereby facilitating access to and operation of our educational collection composed of scientific experiments and audiovisual resources, and thus fostering interaction among students of education, basic researchers and teachers, all graduate students from the Program in Science Education and Mathematics (PPGECIM/UFAL).

Results

Studies of the biological sciences and environmental education were developed, as a means of integrating students from the various undergraduate courses at UFAL, in particular those related to promoting improvements in academic performance, and encouraging elementary and high school students to work in future related professions.

The results were reproduced in several articles on science teaching practice (ARAÚJO et al., 2011; OLIVEIRA et al., 2011; SOUZA et al., 2011), biodiversity (LIMA JÚNIOR et al., 2012; SOUZA et al., 2013), and youth and adult education (SOUZA et al., 2011; SOVIERZOSKI et al., 2014). The aspects of science education and marine biodiversity of Alagoas, including conservation and environmental education, directed to basic education, and produced by the research group on Benthic Communities of UFAL are available on the site (http://www.icbs.ufal.br/grupopesquisa/comunidadesbentonicas).

6. What we know about the biodiversity of coastal ecosystems on Alagoas

Coordinators: Monica Dorigo Correia and Hilda Helena Sovierzoski, UFAL

Objectives

The aims were to increase knowledge of biodiversity in the coastal ecosystems of Alagoas State, and spread scientific information on the conservation of reefs, estuaries, mangroves and beaches by the general public, with emphasis on teachers and students in public schools.

Description and Conceptual background

This Project, which was initiated in 2012, in Alagoas State, was based on extension activities that concentrated efforts towards the transmission of knowledge about biodiversity in Alagoas coastal ecosystems.

Marine biodiversity calls for the conservation of Alagoas State coastal ecosystems, which are poorly understood and rarely reported on in elementary and high schools. The information generated and gathered by the Research Group on Benthic Communities served as the base for divulging knowledge and activities in environmental education, as directed to coastal conservation. This project involved undergraduate students from Biological Science courses with grants by CNPq/PIBIC, as well as undergraduate students from the programs of Teaching Science and Mathematics (PPGECIM), and Biological Diversity and Conservation in the Tropics (PPGDIBICT), all associated to the Sector of Benthic Communities of the Federal University of Alagoas.

Results

Studies were in the field and the laboratory, with the qualitative and quantitative analysis of the biodiversity and environmental education of the Alagoas coast. It was concentrated on undergraduate and graduate courses at UFAL, in particular those related to marine biology. The aim was to promote improvements in academic performance, and encourage basic and high school students to consider marine science as a future work-option.

Scientific results were divulged in several papers on the biodiversity and coastal ecosystems of Alagoas State, and included topics such as reefs (OLIVEIRA; CORREIA, 2013a; OLIVEIRA et al., 2014; SILVA et al., 2013b), mangroves (OLIVEIRA et al., 2012; SOVIERZOSKI et al., 2014), and environmental education (PEDRINI et al., 2014b). Information on aspects related to the conservation of coastal ecosystems and biodiversity of the Alagoas coast, including several new and endemic species, as well as publications on environmental protection that have been produced by this research group, are available on the site (http://www.icbs.ufal.br/grupopesquisa/comunidadesbentonicas).

7. The Emancipatory Environmental Education by Marine Ecotourism - EcoTourisMar Project

Coordinator: Alexandre de Gusmão Pedrini, IBRAG / UERJ

Objectives

The main objective of this Emancipatory Environmental Education (EEE) project is to offer tourism products with environmental and economic sustainability. Focus is placed on: a) environmental managers and analysts from government agencies that grant licenses to enterprises operating in protected areas of sustainable use; b) tourism and ecotourism entrepreneurs involved in developing economic activities with social and environmental sustainability; c) educators seeking alternative work activities, other than the present that negatively impact the environment.

Description and Conceptual Background

Economic activity derived from Brazilian tourism is mostly a repetition of the wild-capitalist model (unfair and oppressive). This typical model of mass tourism concentrates income among entrepreneurs, while leaving only crumbs, in the form of jobs, to the employees. These are often seasonal and deprived of social security and labor rights (LOUREIRO, 2006). It falls to the underemployed community of disproportionately low income, the option of acquiring tourist products that are in no way socially or financially mitigatory. Beyond incoming taxes, the local government apportions the entire positive income of the receiving infrastructure. Concomitantly, when appropriating both marine and coastal resources, tourists usually generate disastrous social and environmental effects, with a consequential and overwhelming impact on coastal and marine biodiversity (PEDRINI et al., 2007; SILVA; GHILARDI-LOPES, 2012; TUNALA et al., 2013). Thus, Emancipation Environmental Education (EEE) is indispensable as a structuring strategy for promoting drastic changes in the behavior and attitudes of active coastal-tourism enterprises (PEDRINI et al., 2011; PEDRINI et al., 2013b; RHORMENS; PEDRINI, 2015). The facile availability of ecotourism products with features directed to the marine environment (GARROD; WILSON, 2004; GARROD et al., 2002; GARROD et al., 2003) undoubtedly enhance the circumstances of those politicians and financiers alike, involved in activities that devastate the sea (PEDRINI et al., 2011.

The conceptual and operational paradigm of EEE (PEDRINI; BRITO, 2006; PEDRINI et al., 2015a; PEDRINI et al., 2013a; PEDRINI et al., 2011; PEDRINI et al., 2012; PEDRINI et al., 2010; PEDRINI et al., 2014b; RHORMENS, 2013; RHORMENS; PEDRINI, 2015) has been discussed by several authors. They propose that environment education be considered as EEE by marine ecotourism, and that it be characterized as: a) emancipatory; by facilitating the transformation of social actors from illegal citizens into productive ones, thereby involving them in the ecotourism product, and generating their partial financial or overall independence, for example, as entrepreneurs or guides; b) transformative; by allowing those involved in the application of the product to acquire knowledge and skills through experience, thus enabling them to face, solve and prevent environmental problems, including those from the region of the ecotourism route; c) comprehensive; by placing all or most of the social actors in the area under the influence of product application; d) globalizing, addressing the environment to its various local, regional, national and global scales; e) contextualizing; in which the action is based on knowledge of local reality in which there is ecotourist activity; f) interdisciplinary; since, as environmental issues evolve over time, they are essential for the aggregation of knowledge in problem solving and improvements; g) ethics; with respect for all planetary life-forms, especially those in the ecotourism route region; h) permanent; since episodic action leads to disruption of the instructional process, and disengagement of the citizens involved; i) participatory; in that citizens, on acquiring knowledge about the entire product creation process, can opine from experience and so contribute towards product-improvement.

This model will generate compatibility between political action and survival, thus giving rise to a unique ecotourism product that presents the following characteristics: a) limitation to 10 participants (PEDRINI et al., 2011); b) equitable sharing of the financial benefits thereby generated; c) occurrence in a natural environment involving the local community; d) inducing discussion on contextual socio-environmental subjects (environmental performance); e) entire social and environmental protection as the end result (PEDRINI et al., 2011). Thus, a marine ecotourism product could be a feasible substitute for massive and predatory tourism in the marine environment (GARROD; WILSON, 2004; GARROD et al., 2002; GARROD et al., 2003).

Results

Table 4 presents the adopted methodological model with its main steps (PEDRINI et al., 2011).

Although two products were formulated on a research scale, the only one appropriately tested as a possible commercial product was snorkel-diving. Both products attract tourists worldwide. The first was launched in the Marine Environmental Protection Area of Buzios (APAMAB), Rio de Janeiro State. The town of Buzios includes a seaside resort with very beautiful beaches. However, of late the town has been receiving visitors from ocean-going cruisers that disembark thousands of passengers, just to spend the day on the beach. As meals are aboard ship, little use is made of local resources, and the town only receives by-products from such a massive and socially exclusive tourism. Fishermen have sold their instalations, and gone to live on the outskirts. Thus, involvement of the local community has not been possible as was desired. However, the local state school has formed tour guides recognized by the Ministry of Tourism and the project has become a discipline in the course (PEDRINI et al., 2011; PEDRINI et al., 2012).

The second Ecoturismar product was developed in the Environmental Protection Area of Tinharé and Boipeba Islands (EPATB), Cairu county, Bahia State. There, mass tourism occurs mainly in the form of coral-reef visits, resulting in clearly noticeable adverse effects. The test results were: a) selection of Tassimirim beach, with variated marine geobiodiversity, for deploying an underwater trail 320 meters long; b) product testing with 28 participants: 89% rated the product as excellent; c) 76% of the tourists are agreeable to paying $ 17.00 to $ 33.00 for the product; d) 80% of the residents classified the product as excellent; e) 91% would like to get involved with the product; f) 88% of local entrepreneurs rate the initiative as excellent; g) 55% of these would divulge the product; h) The price of the product is now $ 16.00. Income from the product applied during 10 days generated $ 433.00. If association holds, around 50% of the income would go to pay the diver and project technical coordinator, with almost 100% profit.

Table 4. Main steps of the model which facilitates the development of Emancipatory Environmental Education through Marine ecotourism.

Steps	Model subtopics
1	Characterization of negative public use of marine ecosystems, by quantifying them through comparative studies or direct observation
2	Characterization of marine geobiodiversity and design of a trophic contextual web
3	Creation of a network of partners interested in supporting or owning the product after its formulation, with agreement on ways of collaboration
4	Product formulation, including an underwater trail with interpretative areas
5	Product efficacy assessment generated by the university
6	Training courses offered to divers and micro-entrepreneurs from the local community
7	Dissemination of results to the scientific community, and the procedure towards a network of local partners.

8. Project PEAPP: Perception and Environmental Education in a Public Square, as a strategy to face Sea Global Warming

Coordinator: Alexandre Gusmão Pedrini, IBRAG / UERJ

General objective

Develop a methodology for keen perception, as an environmental and educational form of applying extension activities of UERJ, with the context of a material detachment event that occurs in a public square denominated Edmundo Rego in the city of Rio de Janeiro.

Specifics objectives

Environmental perception

The main objectives are: a) identify perception of climate change, especially global warming (GW) at sea, among children, teenagers and adults; b) test the hypothesis whether visitors to the square and the material detachment event have a higher level of socio-environmental knowledge than mere bypassers; c) check the level of understanding of the real significance of certain selected key-concepts, viz., the environment, the marine environment, Global Climate Change (GCC), the effects of sea global-warming, and the causes of GW; d) evaluate which media are important as sources of information on the studied subjects; e) check whether the subjects know who is responsible for GCC; f) learn whether visitors assume a participating attitude and adaptation to GCC.

Environmental Education

The main objectives are: a) develop a methodology for promoting environmental education to face global warming in a marine environment within the context 'Climate Change', among teens and adults who are visiting a public square; b) due to contextual difficulties, through 'Participatory Planning' select which are the appropriate methodological strategies for environmental education action in the place chosen; c) test each of the chosen strategies, as to suitability and performance; d) present the composition of the marine environment, its importance and synergy, and the negative effects of Global Warming; e) Encourage and discuss, what each can do, both individually and collectively, to address the negative effects of GW at sea.

Description and Conceptual Background

Environmental education, as a strategy for coping with GCC, more specifically those arising from Global Warming, and their impact on the sea, is in the very beginning. Vasconcelos and TAMAIO (2010) strongly criticized the National Climate Change Plan developed by the Ministry of the Environment, for encouraging improvements in education in this area. The federal government subsequently published an interesting book on the subject written by TAMAIO (2013). This very preliminary work presents several guidelines on the way the environmental educator should address GCC. One is to provide scientific information on identifying the phenomenon and its anthropogenic causes. He selected certain authors and sites identified with the EE chain defended by him. Unfortunately, in the process such works as those by PEDRINI (2008) and PEDRINI and SABA (2008) among others, and as presented in this article, were excluded.

In fact, in Brazil there is the lack of a comprehensive synthesis of convergence between EE and GCC. The practical character of the process is presented by VIEIRA and BAZZO (2007), DEBONI (2007) and PEDRINI and SABA (2008). The first reports on a case of EE with GW in the classroom, showing scientific methodology with a strong epistemological component. The second is that by PEDRINI and SABA (2008), originally written in English. They proposed a methodology for addressing the main problem arising from GCC, i.e., Global Warming (GW). Work was carried out in three steps, in six classes directed to the first and second years of High School. It was the basis of research for the film "An Inconvenient Truth" presented by the former USA Vice President Al Gore. The third, by DEBONI (2007), presented reflections on issues arising from global change (also centered in GW) and EE. This involved a series of conjectures on EE and the media, thereby proposing that environmental educators go deeper into the subject in theoretical and conceptual terms, and not be limited to a repetition of what has been seen on TV or in films, such as "An Inconvenient Truth", with its plainly visible characteristics of self-promotion.

In fact, DEBONI (2007), besides undertaking research in the field, incited government officials to assume their responsibilities for more in depth studies of this delicate problem within the context of Brazilian environmental education, whence the subject requires the comprehensive training of the public, teachers, politicians, public authorities, etc. The contribution of this project arises from reaching the public that congregates at a material detachment event in a public square. Thus, this extension work addresses GCC to a congregation in a public space, as understood from the Habermas perspective (HABERMAS, 1984), viz., a *locus* for collective claims, both by adults and teenagers.

Results

For PEDRINI et al. (2014a) and from preliminary results, it was shown that most people (75%) correctly comprehend the concepts Marine Environment (ME), Global Climate Change (GCC) and Global Warming (GW). On the other hand, Environmental Education (EE) is only understood as a change in behavior (59%). The understanding is that humanity is the social-actor responsible for GCC (72%). People believe that they help to improve the environment, a) by becoming aware of the problem, and aiding in conservation (23% each), and b) by practicing the three Rs (17%). In the case of 22%, there was no response. The fact that 1/5 stated that nothing should be done requires investigation. The results of diagnosis imply an in-depth approach to the subject of the consequences of GW on the sea.

As to responsibility for GCC, Pedrini et al. (PEDRINI et al., 2015c) verified whether respondents attributed this to humanity as a whole. However, it is important to point out that there are more important social actors to be highlighted, apart from those indicated in this naïve answer. These are unscrupulous entrepreneurs and selfish investors, who only think about constantly increasing their profit. In general, these groups attempt to cheat environmental control systems, and have no scruples about worsening the environmental health of cities and their outskirts. Assign the deterioration of environmental quality by GCC to mankind as a whole could, to a certain extent, be a form of accommodation on the part of respondents, as also a translation of the consumerist-capitalist-media maneuvers that crown our contemporary society. Another alternative is a way of attributing responsibilities to nobody in particular, and thus conceal the real and mainly responsible culprits, in other words, the rich industrial countries.

Some believe that only individual change would suffice for confrontation with GCC (GHILARDI-LOPES et al., 2014a; GHILARDI-LOPES et al., 2015). However, it has been shown that the simple acquisition of fresh knowledge is insufficient to generate these changes (TAMAIO, 2013). PEDRINI et al. (PEDRINI et al., 2015b; PEDRINI et al., 2015c) showed that there are no daily individual attitudes. The general belief was that collective efficacy would only be attained through the implementation of mediating, public policies. Neither do they know that government planning is more concerned with plans for adjustments to the situation, and less to facing and situating changes. Furthermore, the existence of federal, state and municipal policies in the City of Rio de Janeiro is unknown, and there is no assessment of their efficacy. This accommodation, even among environmentalists, is worrying. A possible explanation could be discredit in a government official who might be the leading figure in formulating laws derived from policies. The sources of information about GCC is one more topic of concern. The predominant ones are Internet (32%) and cable TV (21%). It is widely known that, to a large extent, data from both are either wrongly divulged or outdated. Nonetheless, the hypothesis about GCC tested by environmentalists in the square having an adequate information level, has been statistically proven. However, on coping with GCC, this information-set cannot be translated into terms of attitudes in the daily lives of individuals.

The method on how individuals could face and contribute towards solving the adverse effects of GCC presented relative dispersion. Thus, it can be deduced that the public in general knows nothing about what and how to act. The belief (reinforced by the concept of EE being merely behavioral, see PEDRINI et al., 2015b) is that only the adoption of essentially behavorial action of the three Rs, or eventual simple action, are adequate.

9. Diving in Seropedica's education

Coordinator: Valéria Marques, UFRRJ, Guilherme Henrique Pereira Filho, UNIFESP

Objectives:

This Project was started during 2011, with an interdisciplinary and interdepartmental character integrating teachers and students belonging to several fields of knowledge, notably biology and psychology. It was afterwards split into two sub-projects "Diving, the connection between Seropedica and UFRRJ: the use of narration in environmental education" (SILVA; MARQUES, 2012; VERAS et al., 2012; VINHAES et al., 2012) and "Dive and ideas, innovation and ideals" (MARQUES et al., 2013). Within the overall aim of linking high school students to the university scientific environment, thereby favoring new possibilities in knowledge construction, the first was directed towards collaboration with teachers, by enriching practical pedagogy through diving experience, and evaluating narration as a methodological tool. The second was aimed at evaluating the use of underwater trails, as an educational activity in high schools (CIEP 155 Maria Joaquina de Oliveira Seropédica/RJ). It was developed in two phases, viz., the training of environmental monitors/multipliers, and the evaluation of the diving experience of students (Ilha Grande, RJ), through questionnaires and interviews.

Results

1. Development of protocols and implementation of 3 trails: "In loco" Ilha Grande terrestrial and underwater trails; Itinerant trail, in which the marine environment was discussed through comic strips in 10 panels; Virtual electronic track (under development).
2. Development of supporting didatic material (MARQUES; PEREIRA FILHO, 2013; MARQUES et al., 2013).
3. Monitor training and formation –6 high school teachers and 11 monitors were formed.
4. Model implementation – application to 25 high school students (2011-2012) and 75 students (2012-2013).

5. Evaluation of activities – the discussion and activity evaluation were published as abstracts (MARQUES et al., 2013; SILVA; MARQUES, 2012; VERAS et al., 2012), and as an undergraduate dissertation (VERAS, 2014). A master dissertation is also in preparation.

10. Mussels: Evaluating and stimulating community integration coupled to mussel farming at Jurujuba, Niterói – Rio de Janeiro

Coordinators: Daniel Shimada Brotto, Marcia Esteves Capello, Lucilia Ramos Tristão, UVA; Marli Cigagna Wiefels, UFF)

Objectives

The main goal is to evaluate socio-environment perception, and various forms of production of those directly and indirectly involved in mussel farming, prior to implementing advisory action aimed at optimizing both activities and social emancipation.

Description and Conceptual Background

Although handicraft fishing, tourism and sea farming can be considered as natural local vocations, there have been many problems since the end of the 70's, evidently brought about by the lack of understanding on the part of government authorities. The formerly traditional fishing community is now a decadent and disorderly town district, composed of seafood restaurants, and decrepit sardine canning industries, commercial fishing docks, yachting marinas and mussel farms, in other words, a diversified human community mainly composed of lower income citizens (RITTER, 2007).

Since the end of the 80's, mussel farming emerged as a profitable and economic activity in the region, nowadays this being the main source of income that sustains many families, independent of the questionable water conditions, the lack of organization, and the technological gap among local entrepreneurs.

Project approach is quite in accordance with the precepts of Environmental Education for Sustainable Societies (PEDRINI; BRITO, 2006), by aiming at self-emancipation and the integration of individuals by permanent participation in the solution of on-the-spot environmental questions.

Preliminary results

As they belonged to families of mussel farmers and fishermen, the primary focus was centered on a group of school students in the region. At the end of 2011, and after a first contact with teachers and the director of the CEFEM (Colégio Estadual Fernando de Magalhães), students were invited by their teachers to participate in environmental education activities, specifically beach surveys and rapid assessment protocols, carried out in the neighborhood, and also to attend extra school lectures, when they were asked to respond to questionnaires, to so evaluate perception and the efficacy of the specific activity. Those directly involved in mussel farming were informally interviewed and observed *in situ* during working hours.

Results from the aforementioned approaches should be considered, when planning instructive activities focusing the optimization of mussel farming at Jurujuba, and of the use of discarded shells in handcraft and the arts. The implicit aim is to foment critical perception of the world, as well as community integration, focusing on a certain charismatic living marine resource, since in Brazil the word mexilhão (mussel) can be used to define, not only an inquisitive and restless person, but also another important aspect of the cultivated mussel species, *Perna perna*, a very resilient invasive species that was accidentally brought to South America in slave ships from Africa, as were the ancestors of most of the people living in Jurujuba.

CONCLUSIONS

Marine and coastal environment-education activities in Brazil are still scarce and need to receive effective support from such integrated networks as ReBentos, which unite researchers from various regions of the country, thereby facilitating the creation of sub-networks and the exchange of information, data and results. There are several models of Marine Environmental Education under way. They differ mainly as to the theoretical approach (PEDRINI, 2008; PEDRINI, 2013), as for example, being in accordance with the theory of Popular Education by Paulo Freire, or with Critical Environmental Education. They also vary in the methodological strategies selected to obtain data or their analysis (PEDRINI, 2007) such as the selection of action research, interviews, life histories, questionnaires, and content or speech analysis, among others. What can be standardized over short-term are data-analysis methods in the context of a quantitative paradigm, since within the qualitative, standardization would only be possible after numerous actions and projects have been completed. Only in this way is it possible to think of establishing standardized procedures based on a solid conceptual framework.

So far, the ReBentos environment education work-group is dealing with activities and projects that still do not use the biologic results from the other groups of the network (estuaries, beaches, submersed vegetated bottoms, reefs and rocky shores, mangroves and salt marshes). The aim is to increase the use and exchange of these data in the future. Actions should be expanded to public schools, as well as to other states within the country. EE approaches with the specific goal of impacting decision-makers and media are also considered fundamental.

ReBentos Directives for Marine-Environment Education

Climate change is an excellent pedagogical opportunity for inducing desirable outcomes in environmental education. It serves as a means for teaching the science of complex systems, and comprises a teaching opportunity for meaningful learning, through being ideal for debating the application of the precautionary principle. Nonetheless, the complexity and global nature of the phenomenon, associated with the difficulty of modifying human behavior, complicates the choice of efficient strategies in climate-change education. Therefore, the evaluation of medium and long-term education intervention is crucial. Besides the number of participants or events, evaluation should be based on achievement of specific environmental education indicators.

As a further step, definite protocols should be elaborated for each EE model, to so serve as supports for newcomers to the area, and for direct action within the network, thereby facilitating the exchange of experience and material among ReBentos groups.

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