

# Increased anthropogenic pressure decreases species richness in tropical intertidal reefs



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## ABSTRACT

Multiple human stressors affect tropical intertidal sandstone reefs, but little is known about their biodiversity and the environmental impacts of these stressors. In the present study, multiple anthropogenic pressures were integrated using the relative environmental pressure index (REPI) and related to benthic community structure across an intertidal gradient in five sandstone reefs in the tropical South Atlantic coast. Greater species richness and diversity were noted in the low intertidal zones. There was a negative relationship between REPI and species richness, suggesting that increasing anthropogenic pressure has decreased benthic richness. The factors associated with the loss of richness were jetties built to control erosion, urban areas, beachfront kiosks and restaurants, fish markets, and storm sewers with illegal sewage connections. Our results highlight the need for better infrastructure planning and rigorous monitoring of coastal urban areas, since the large influence of multiple human pressures in these reefs leads to biodiversity losses.

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## 1. Introduction

The assessment of reef communities and anthropogenic pressure is considered a worldwide priority, with the aim to formulate effective conservation policies (Halpern et al., 2012); however, this remains an unsolved problem (Johnston and Roberts, 2009). Tropical reefs have high biodiversity and productivity, and provide diverse environmental services (Tittensor et al., 2010). Despite their importance, these ecosystems are among the most threatened in the world (Halpern et al., 2007; Mora et al., 2013; Palumbi et al., 2014).

Studies on anthropogenic pressure commonly relate changes in biological communities with a single factor such as human population density or the percentage of urbanized land (Alberti et al., 2007). However, this approach does not provide a broad view of multiple anthropogenic pressures. For example, Oigman-Pszczol

and Creed (2011) pointed out that only a few studies have simultaneously evaluated multiple biological descriptors and anthropogenic pressures. For this reason, these authors proposed a method that combines heterogeneous pressure factors within a single index, the relative environmental pressure index (REPI). This index can be useful when analyzing impacts in the structure of benthic assemblages.

The influence of anthropogenic pressure is typically assessed using biological indicators (Goodsell et al., 2009). Sessile benthic organisms respond directly and quickly to changing environmental factors (Orfanidis et al., 2001, 2003), and thus are considered excellent indicators of anthropogenic modifications (Gall et al., 2016; Orfanidis et al., 2001, 2003). Use of the anthropogenic pressure index (an aggregation of multiple factors) and its association with benthic communities is important, but such knowledge remains scarce for the Tropical Southwestern Atlantic coast. Moreover, relatively few studies related to anthropogenic influences have been conducted in tropical and temperate environments in general (Martins et al., 2012; Oigman-Pszczol and Creed, 2011; Oliveira et al., 2014).

The Tropical Southwestern Atlantic coast contains diverse habitats, including coral reefs, intertidal sandstone reefs, sand beaches,

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and dunes. The area has a tropical wet and dry climate in the east, and a semi-arid climate on the northern coast, with a very stable annual seawater temperature ranging from 27 °C to 29 °C (Dias et al., 2013). Intertidal sandstone reefs differ from typical rocky shores and tropical coral reefs mainly by their gentle slope and sandstone composition. Substantial research has been conducted on coral reefs and rocky shores, but little is known about the benthic communities of tropical intertidal sandstone reefs (Leão et al., 2003, 2010; Rabelo et al., 2015).

Despite the socioeconomic and ecological importance of tropical intertidal sandstone reefs, there is a knowledge gap in the scientific understanding of reef biodiversity and its response to multiple anthropogenic pressures. The aim of the present study was to incorporate different anthropogenic pressures using the REPI and relate them to species richness, Shannon's diversity, and Pielou's evenness in intertidal sandstone reefs located in coastal Ceará, Brazil (Tropical Southwestern Atlantic, *sensu* Spalding et al., 2007). The Tropical Southwestern Atlantic coast is rapidly transforming due to recent intense urbanization (Marchese, 2015; Selig et al., 2014) with a recent increase in cumulative human impact (Halpern et al., 2015).

The goal of the study was to address the following questions: (1) Are there differences in the structure of sessile benthic communities between different intertidal zones and between intertidal sandstone reefs? (2) Do species richness, evenness, and diversity decrease as REPI increases? (3) What anthropogenic pressures may influence the structure of sessile benthic communities?

## 2. Materials and methods

### 2.1. Study area

The study was conducted in five intertidal sandstone reefs distributed along the west coast of the state of Ceará, Brazil, in the Tropical Southwestern Atlantic (Fig. 1). The intertidal zones of this coast consist of sandstone reefs and beach rocks, which are rocky outcrops with flat surfaces that are tilted slightly seaward (Rabelo et al., 2015). The reefs were formed by the erosion of cliffs and

belong to the Barreiras Stratigraphic Group (Maia, 1998). The Barreiras Group is a terrigenous sedimentary cover that formed during the Miocene to Early Pleistocene, and is widespread along the Brazilian coast (Vilas Boas et al., 2001).

The reefs are located west of Fortaleza, the capital of Ceará, located in northeastern Brazil. Fortaleza's population has increased in recent decades to approximately 2.55 million, with a population of over 3.5 million in the overall metropolitan region (Garmany, 2011; Zuquette et al., 2004).

All sandstone reefs studied are gently sloping (maximum slope value: 2°, measured in the field) and have similar exposure to waves and winds, accessibility and a semi-diurnal tidal regime.

### 2.2. Sampling procedures

Qualitative and quantitative sampling of sessile benthic communities in tropical intertidal reefs was conducted using a non-destructive photo-quadrat method. Five intertidal reefs were sampled during the dry season (late October and early December 2013) during low-water spring tide, an approach similar to that in Oigman-Pszczol and Creed (2011), which also collected over a period to assess the influence of anthropogenic stressors. All species were identified in the lower taxonomic levels genus and species. The identification of algal genus and species was carried out using an optical microscope with reference to a specialized bibliography, and was compared to material deposited in herbariums, with nomenclature following the guidelines of Guiry and Guiry (2016).

In each intertidal reef, a central region was georeferenced, delimiting a 100 m × 90 m area parallel and perpendicular (in length) to the coast. Subsequently, this length was divided into three intertidal sub-zones (Rabelo et al., 2015; Rosa-Filho et al., 2009): a high zone (90 m–60 m), mid zone (60 m–30 m), and low zone (30 m–0 m), measured from the low limit of the intertidal zone. In order to have 30 samples from each reef for quantitative analyses, each intertidal sub-zone was sampled with 10 photo-quadrats (Gotelli and Ellison, 2011) measuring 2500 cm<sup>2</sup> (50 cm × 50 cm) each, which were randomly positioned using a

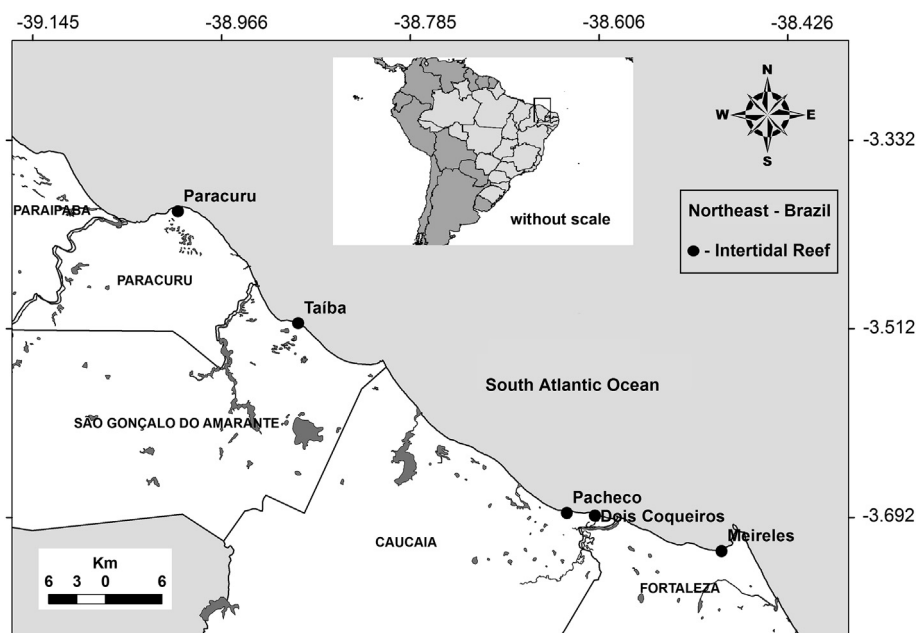


Fig. 1. Location of the reefs sampled distributed along the west coast of the state of Ceará, Brazil, in the Tropical Southwestern Atlantic.

Cartesian plot (100 m × 20 m) (Martins et al., 2012; Pridmore et al., 1990). Each photo-quadrat was divided into 100 sub-quadrats (5 cm × 5 cm) with 100 fixed points of intersections. The intersection point method was used to analyze the presence and coverage of species (Floeter et al., 2007). To complement the characterization of the reefs, unconsolidated (sand) and consolidated substrates were quantified to assess the area without biological cover (Oigman-Pszczol et al., 2004).

Data on the percentage of coverage by species and on the substrates (consolidated and sand) were tabulated for the intertidal sub-zones (high, mid, and low) and reefs (Meireles, Dois Coqueiros, Pacheco, Taíba, and Paracuru) for comparison. The species richness, Shannon-Wiener diversity index ( $H'$ , using  $\log_e$ ), and Pielou's evenness ( $J'$ ) were calculated. Percentage coverage data were used to calculate  $H'$  and  $J'$ . These indices are commonly used to assess anthropogenic impacts on marine communities (Johnston and Roberts, 2009).

### 2.3. Urban area and REPI analysis

The percentage of urban area coverage was calculated for a 15-km-long and 10-km-wide area measured from the center of each reef using maps. A 150-km<sup>2</sup> area for each reef was chosen based on whether the environment surrounding the reefs, tributaries, and estuaries was urbanized, according to the methodology of Oigman-Pszczol and Creed (2011). A field survey was conducted to quantify the number of man-made coastal structures located on the beaches of each reef, and the REPI was calculated for each reef using the weighted arithmetic average of the pressures (Oigman-Pszczol and Creed, 2011). The anthropogenic pressures that may affect the sessile benthic communities were defined in the field. The REPI (multi-metric index) includes the percentage of urban areas, number of beach kiosks and restaurants, jetties, fish markets, storm sewers, ports, and the number of fishing sheds. Compared to the original definition of the REPI (Oigman-Pszczol and Creed, 2011), this study excluded the pressures that varied in frequency and intensity throughout the year, such as the presence of waste at the beach, recreational activities (diving and sunbathing), and presence of fishing vessels.

### 2.4. Statistical analysis

To assess the similarity between the reefs and intertidal sub-zones, a cluster analysis was performed using the unweighted pair group method with arithmetic mean (UPGMA) method, which was based on the Bray-Curtis dissimilarity index (Bray and Curtis, 1957; Oksanen et al., 2016; Valentin, 1995). The data were transformed using  $\log_e(x + 1)$  to reduce the effect of dominant species and the number of zeroes in the dataset. The fit between the dissimilarity matrix and dendrogram was assessed using the cophenetic correlation coefficient ( $r$ ) (Sokal and Rohlf, 1962). After the groups were defined, indicator value (IndVal) scores were used to identify indicator species in each group.

PERMANOVA analysis was used to compare the sessile benthic community structure between the reefs and intertidal sub-zones. PERMANOVA was chosen because of the lack of various macroalgae species in a large number of samples, since this statistical analysis method is relatively less sensitive to the presence of zeroes (Anderson, 2001; Legendre and Anderson, 1999). In addition, this analysis is recommended when response variables (i.e., abundance of macroalgae species) may be correlated (Anderson, 2001; Legendre and Anderson, 1999), which may be relevant for this study because of the taxonomic redundancy in some groups.

We also used EcoTest.sample, a randomization test for the statistical comparison of two or more sample-based rarefaction

curves, to test the ecological null hypothesis that samples, represented by incidence data, were drawn from the same assemblage (Cayuela and Gotelli, 2015; Cayuela et al., 2015). Rarefaction curves with their respective confidence intervals (95%) were also calculated. The rarefaction curve is calculated based on the presence of species in the samples. This calculation does not use the full species richness or average, but is rather based on the incidence of each species per site.

The relationship between the richness of the benthic communities and REPI was estimated by linear regression. Additionally, an exploratory approach on scatter plot was used to verify possible relationships between the REPI and Shannon-Wiener diversity index and Pielou's evenness as well as relationships between individual anthropogenic pressures and species richness with the data transformed using  $\log_e(x + 1)$ .

All analysis were conducted in R version 3.1.1 using the packages “rareNMtests” (Cayuela and Gotelli, 2015; Cayuela et al., 2015), “vegan” (Oksanen et al., 2016), “labdsv” (Roberts, 2016), and “car” (Fox and Sanford, 2016). The level of significance was established at 5%.

## 3. Results

### 3.1. Sessile benthic community structure of intertidal reefs

A total of 24 sessile taxa were observed, most of which were marine macroalgae. Additional fauna included the mollusk *Brachidontes exustus*, the crustacean *Chthamalus bisinuatus*, the polychaete *Phragmatopoma caudata*, and the colonial cnidarians *Siderastrea stellata* and *Zoanthus sociatus* (Table 1). The high reef zones had a higher coverage of the algae *Ulva lactuca*, *Ulva flexuosa*, and *Cladophora* sp., as well as the mollusk *B. exustus* and the crustacean *C. bisinuatus*. The mid and low reef zones had higher coverage values for the algae *Sargassum vulgare*, *Centroceras clavulatum*, *Chondracanthus acicularis*, *Gracilaria intermedia*, and *Hydropuntia caudata*, as well as the polychaete *P. caudata* and the colonial cnidarians *S. stellata* and *Z. sociatus*. These results suggest this zonation for all the reefs studied, except for Meireles (Table 1). We observed that the coral *S. stellata* was dominant in the low zone of the Meireles and Dois Coqueiros reefs. By contrast, in the Paracuru reef, the low zone of the reef was dominated by *S. vulgare* (Table 1).

The highest percentage of consolidated substrate (without biological cover) was observed in the two reefs near Fortaleza (Meireles and Dois Coqueiros). The data demonstrated a gradual increase in the percentage of unconsolidated substrate when moving westward from the coast (Table 2). The reefs with the greatest species richness, diversity, and evenness were Taíba and Pacheco (Table 3). The lowest diversity and species richness, as well as the highest evenness, was observed in the Meireles reef, located in Fortaleza city. We identified a significant increase in diversity and species richness, but not evenness, from the high to low zones of all reefs (Tables 2 and 3).

The cluster analysis indicated higher similarity between the Dois Coqueiros and Pacheco reefs (Fig. 2). The dendrogram based on the intertidal sub-zones revealed five groups (Fig. 3): group 1, composed of the Dois Coqueiros and Pacheco reefs, which were grouped according to the high and mid zones; group 2, formed of all zones in Paracuru; group 3, composed mainly of the mid and low zones in the Meireles reefs, but including the low zone in Dois Coqueiros; group 4, composed mainly of the Taíba reef, which were grouped according to the high and mid zones; and group 5, formed by the low zones of the Taíba and Pacheco reefs. The IndVal scores for the zones indicated that 6 taxa served as indicators (IndVal,  $p < 0.05$ ; Table 4). The results of PERMANOVA revealed significant

**Table 1**  
Occurrence of the sessile benthic community in tropical intertidal sandstone reefs (Ceará west coast, Tropical Southwestern Atlantic).

Taxa	Meireles			Dois coqueiros			Pacheco			Taiba			Paracuru		
	H	M	L	H	M	L	H	M	L	H	M	L	H	M	L
<b>Chlorophyta</b>															
<i>Caulerpa prolifera</i> (Forsskål) J.V. Lamouroux, 1809	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0
<i>Caulerpa racemosa</i> (Forsskål) J. Agardh, 1873	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0
<i>Caulerpa sertularioides</i> (S.G. Gmelin) M.A. Howe, 1905	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0
<i>Cladophora</i> sp. Kützing, 1843	0	0	0	0	0	0	0	0	0.6	0	0	0	14.7	0	0
<i>Ulva fasciata</i> Delile, 1813	0	0	0	0	0	0	0	0	0	5.6	11	14.7	0	0	0
<i>Ulva flexuosa</i> Wulfen, 1803	0	0	0	17.9	2.5	0	33.7	5.2	0	0.7	0	0	0	0	0
<i>Ulva lactuca</i> Linnaeus, 1753	0	0	0	7	18.3	0	30.3	18.7	21.3	0	0	0	1.1	6	6.7
<b>Ochrophyta</b>															
<i>Dictyota menstrualis</i> (Hoyt) Schnetter, Hörning & Weber-Peukert, 1987	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0
<i>Sargassum</i> sp. C. Agardh, 1820	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.4
<i>Sargassum vulgare</i> C. Agardh, 1820	0	0	0	0	0	0	0	0	0	0	0	0	0	23.5	49.1
<b>Rhodophyta</b>															
<i>Acanthophora spicifera</i> (M. Vahl) Borgesen, 1910	0	0	0	0	0	0	0	0	0	0	0.1	0.5	0	0	0
<i>Centroceras clavulatum</i> (C. Agardh) Montagne, 1846	0	0	0	0	1.4	30	0.8	1.6	0	1.7	5.5	0	0	0	0
<i>Chondracanthus acicularis</i> (Roth) Fredericq in Hommersand, Guiry, Fredericq & Leister, 1993	0	0	17	0	1.2	0	0	0	6	0	0.9	26.7	0	0	0
<i>Gracilaria intermedia</i> J. Agardh, 1901	0	0	0	0	0	0	0	0	8	0.2	0	8.1	0	0	0.2
<i>Hydroponia caudata</i> (J. Agardh) Gurgel and Fredericq, 2004	0	0	0	0	0	0	0	0	7.9	0	0	2.5	0	0.1	0
<i>Hypnea musciformes</i> (Wulfen) J.V. Lamouroux, 1813	0	0	0	0	0.9	0	0	0	1.4	0.3	0.6	1.7	12.1	21.2	0
<i>Pterocladia bartlettii</i> (W.R. Taylor) Santelices, 1998	0	0	0	0	0	0	0.6	7.5	16.1	0	0	0	0	0	0
<i>Pterocladia caerulescens</i> (Kützing) Santelices and Hommersand, 1997	0	9.9	12	0	0	4.5	0	0	1.1	0	0	3	0	0	0
<b>Angiosperma</b>															
<i>Halodule wrightii</i> Ascherson, 1868	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.5
<b>Cnidaria</b>															
<i>Siderastrea stellata</i> Verrill, 1868	0	0.4	6.1	0	0	1.6	0	0	0	0	0	0	0	0	0
<i>Zoanthus sociatus</i> (Ellis, 1768)	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0
<b>Mollusca</b>															
<i>Brachidontes exustus</i> (Linnaeus, 1758)	0	0	0	0	0	0	0	0	0	27.9	3.6	0	0	0	0
<b>Anellida</b>															
<i>Phragmatopoma caudata</i> Krøyer in Mörch, 1863	0	0	0	0	0	0	0	0	0	0	2.2	14.5	0	0	0
<b>Crustacea</b>															
<i>Chthamalus bisinuatus</i> (Pilsbry, 1916)	0	2.1	13.7	5.4	3.3	0	24	0	0	0	1.2	0	0	0	0

Divisions of the intertidal reef: H = High, M = Mid, L = Low.

differences between the reefs and intertidal sub-zones ( $p < 0.001$ ) as well as interaction between the reef and intertidal sub-zones ( $p < 0.001$ ).

### 3.2. Environmental pressure index, species richness, Shannon's diversity, and Pielou's evenness

The REPI varied between 1.37 and 38.36, and the REPI values increased as the percentage of urban area increased near the reefs (Table 5). The reef environments with the highest REPI were those under higher anthropogenic pressure (Table 5). There was a significant negative relationship between richness and REPI ( $R^2 = 0.82$ ,  $p = 0.03$ ; Fig. 4). After the separation of different anthropogenic pressures, the percentage of urban areas, beach kiosks and restaurants, fish markets, storm sewers, and jetties showed a negative relationship with species richness (Fig. 5).

The rarefaction test (EcoTest.sample) indicated a significant difference in species richness between the reefs ( $p < 0.01$ ). The rarefaction curves revealed the greatest richness in the Taiba and Paracuru reefs and the lowest richness in the Meireles reefs of Fortaleza city (Fig. 6).

## 4. Discussion

### 4.1. Spatial variation of the benthic community structure of sessile organisms in intertidal reefs

The results identified the dominance of marine macroalgae

when compared with the sessile benthic fauna in all of the sandstone reefs evaluated, as well as higher species richness and diversity in the low zone of the intertidal reefs. The low zone has greater contact with seawater and less exposure to air (Rabelo et al., 2015). Therefore, the high zones (e.g., rocky shores) are presumably dominated by the few species that are tolerant to desiccation. *Ulva* and *Cladophora* spp. had higher coverage values in the upper zones of the Dois Coqueiros, Pacheco, and Taiba reefs. The global success and high abundance of *Ulva* species in the high intertidal zones has prompted detailed investigations of their cellular mechanisms (Holzinger et al., 2015). According to Einav et al. (1995), *U. lactuca* is tolerant to temperature variations, as well as to desiccation and variations in salinity levels. However, the mid and low zones had a greater abundance of red and brown algae. The exposure of macroalgae to air for extended periods of time is a stress factor that promotes the development of more tolerant species (Lobban and Harrison, 1994).

Only the Dois Coqueiros reef showed lower values for the descriptors of the communities (richness, diversity, and evenness) in the low intertidal sub-zone. This may be due to the higher percentage of the alga *Centroceras clavulatum* and the coral *S. stellata*. The dominance of *C. clavulatum* compared with other macroalgae in the low zone of the reef resulted in lower evenness, which favored lower diversity in this reef zone. Only the Meireles reef did not show clear zoning, which is probably due to greater environmental degradation in this area.

Our results provide new information, although spatial variation of the benthic sessile community structure in intertidal sandstone

**Table 2**  
Coverage (%) and ecological indices of sessile benthic communities in tropical reefs (Ceará west coast, Tropical Southwestern Atlantic).

Descriptors	Meireles			Dois coqueiros			Pacheco			Taiba			Paracuru		
	H	M	L	H	M	L	H	M	L	H	M	L	H	M	L
Empty consolidated substrate by zone (n = 10)	97.1	85	40.4	50.3	58.2	53.9	5.7	38.9	2.6	9	24.1	16.3	0	0	0
Empty unconsolidated substrate by zone (n = 10)	2.9	2.6	10.8	19.4	14.2	10	4.9	28.1	35	54.6	50.8	11.5	72.1	48.3	37.1
Species richness (S) by zone (n = 10)	0	3	4	3	6	3	5	4	8	6	8	9	3	8	5
Shannon-Wiener diversity index (H') by zone (n = 10)	0	0.59	1.33	0.96	1.14	0.55	1.16	1.10	1.67	0.78	1.56	1.67	0.83	1.08	0.75
Pielou's evenness (J) by zone (n = 10)	0	0.54	0.96	0.87	0.64	0.50	0.72	0.79	0.80	0.43	0.75	0.76	0.75	0.52	0.47
Empty consolidated substrate by reef	74.2			54.1			15.7			16.5			0		
Empty unconsolidated substrate by reef	5.5			14.5			22.7			39			52.5		
Total richness (S)	4			8			11			13			11		
Shannon-Wiener diversity index (H') by reef	1.31			1.58			1.75			1.95			1.38		
Pielou's evenness (J) by reef	0.95			0.76			0.73			0.76			0.57		
REPI	38.36			31.12			23.48			1.37			9.80		

Intertidal sub-zones: H = High, M = Mid, L = Low.  
REPI, relative environmental pressure index.

**Table 3**  
Descriptive data (mean and standard deviation) of Shannon-Wiener diversity index, Pielou's evenness, and species richness.

Reefs/zones	Shannon-wiener diversity index	Pielou's evenness	Species richness
Dois Coqueiros (n = 30)	0.26 ± 0.32	0.38 ± 0.46	1.3 ± 0.7
Low (n = 10)	0.22 ± 0.31	0.32 ± 0.44	1.2 ± 0.8
Mid (n = 10)	0.26 ± 0.33	0.37 ± 0.48	1.4 ± 0.5
High (n = 10)	0.31 ± 0.33	0.45 ± 0.48	1.4 ± 0.7
Meireles (n = 30)	0.10 ± 0.21	0.15 ± 0.31	0.7 ± 0.8
Low (n = 10)	0.24 ± 0.31	0.34 ± 0.44	1.3 ± 0.7
Mid (n = 10)	0.07 ± 0.14	0.09 ± 0.20	0.7 ± 0.8
High (n = 10)	0 ± 0	0 ± 0	0 ± 0
Pacheco (n = 30)	0.64 ± 0.35	0.70 ± 0.34	2.3 ± 1.0
Low (n = 10)	0.78 ± 0.36	0.79 ± 0.30	2.7 ± 1.1
Mid (n = 10)	0.54 ± 0.40	0.59 ± 0.42	1.9 ± 1.2
High (n = 10)	0.61 ± 0.27	0.74 ± 0.28	2.2 ± 0.6
Paracuru (n = 30)	0.29 ± 0.32	0.35 ± 0.36	1.7 ± 1.1
Low (n = 10)	0.34 ± 0.29	0.41 ± 0.31	1.8 ± 0.9
Mid (n = 10)	0.35 ± 0.39	0.38 ± 0.35	2.0 ± 1.5
High (n = 10)	0.18 ± 0.29	0.25 ± 0.42	1.2 ± 0.6
Taiba (n = 30)	0.49 ± 0.45	0.49 ± 0.38	2.0 ± 1.4
Low (n = 10)	0.70 ± 0.48	0.63 ± 0.29	2.9 ± 1.5
Mid (n = 10)	0.51 ± 0.47	0.51 ± 0.45	1.8 ± 1.5
High (n = 10)	0.25 ± 0.31	0.32 ± 0.36	1.4 ± 1.0
Overall total (n = 150)	0.36 ± 0.36	0.41 ± 0.41	1.6 ± 1.2
Low total (n = 50)	0.46 ± 0.35	0.50 ± 0.36	2.0 ± 1.0
Mid total (n = 50)	0.35 ± 0.35	0.39 ± 0.38	1.56 ± 1.1
High total (n = 50)	0.27 ± 0.24	0.35 ± 0.31	1.26 ± 0.58

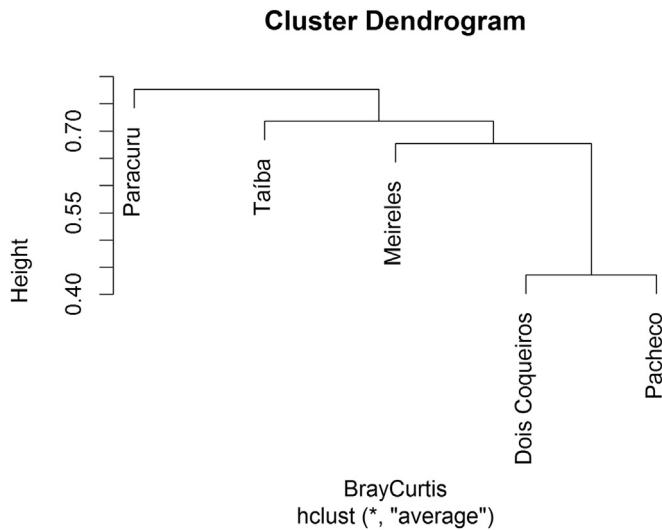
reefs located in the coastal area of Ceará, Brazil (Tropical Southwestern Atlantic, *sensu* Spalding et al., 2007) remains understudied. According to Matthews-Cascon and Lotufo (2006), there is a distinct intertidal zone of algae and various types of animals between the low tide and the supralittoral zone. However, there are few published studies on species composition, abundance, or community descriptors between the different strata of these type of reefs (see Rabelo et al., 2015 for data on zoanthids).

The intertidal reefs of the tropical coast analyzed in the present study exhibited relatively high spatial biological heterogeneity, as shown by the IndVal and cluster analysis. However, there was greater similarity between the Dois Coqueiros and Pacheco reefs, most likely due to their geographical proximity (<5 km) (Fig. 1) and the consequent influence of similar environmental conditions.

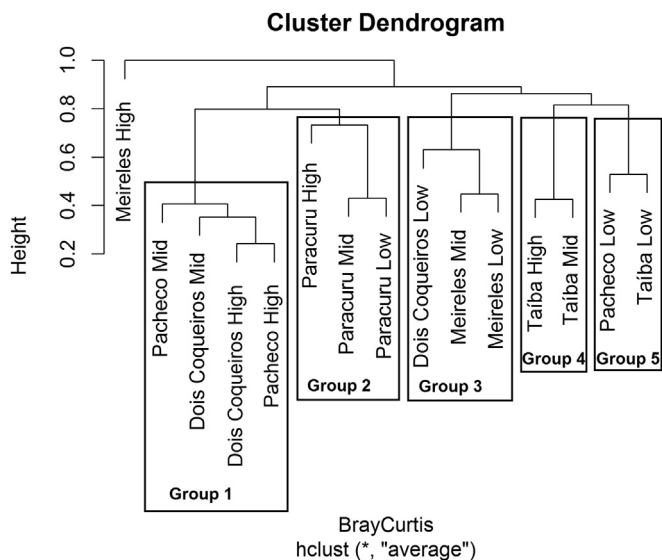
#### 4.2. Relationship between the REPI and species richness, Shannon's diversity, and Pielou's evenness on intertidal reefs

Through this study, we have provided the first demonstration of a significant negative relationship between the REPI and species richness in intertidal reefs of the Tropical Southwestern Atlantic. Oigman-Pszczol and Creed (2011) investigated subtidal rocky shores with a similar aim, but did not find a relationship between the REPI and community descriptors. This difference may be due to the location of our study, which was more exposed to direct anthropogenic impacts (see Table 4).

The species richness showed a significant negative relationship with the REPI. Previous studies found similar results for richness in intertidal communities of other reef types (Johnston and Roberts, 2009; Scherner et al., 2013). Anthropogenic pressure tends to



**Fig. 2.** Cluster analysis (UPGMA) between the sample areas by species inferred from the Bray-Curtis dissimilarity index (transformed data:  $\log_e(x + 1)$ ). The cophenetic correlation was 0.84.



**Fig. 3.** Cluster analysis (UPGMA) between the strata of the sampling areas per species inferred from the Bray-Curtis dissimilarity index (transformed data:  $\log_e(x + 1)$ ). The cophenetic correlation was 0.86. The high zone of the Meireles reef was removed from the clusters due to the absence of species.

remove certain particularly vulnerable species entirely; thus, species richness seems to be the most sensitive indicator of human impact in these environments. This study identified a reduction in the richness of species, but the relative abundance of species was proportional or the same, resulting in overall increased evenness. For example, in the Fortaleza reef (the area with the highest REPI), species richness was lower, but evenness was high, with the few species present showing similar abundances. Scherner et al. (2013) showed that the relationship between certain aspects of urbanization and ecological indices was stronger and more significant in the following ascending order: Pielou's index, Shannon-Wiener index, and species richness. According to Wells et al. (2007), a decrease in species richness may demonstrate the loss of ecological quality from ecosystems. The large-scale consequences of biodiversity loss are unknown, but the potential recovery, productivity,

**Table 4**

Results of indicator value (IndVal) analysis in relation to the groups defined according to the Bray-Curtis dissimilarity index by intertidal sub-zone.

IndVal result			
Species	Group	Indicator value	Probability
<i>Ulva flexuosa</i>	1	0.97	0.002
<i>Siderastrea stellata</i>	3	1.00	0.010
<i>Pterocladia caerulensis</i>	3	0.81	0.016
<i>Brachidontes exustus</i>	4	1.00	0.026
<i>Hydropuntia caudata</i>	5	0.99	0.016
<i>Gracilaria intermedia</i>	5	0.97	0.037

and maintenance of the ecosystem, as well as water quality, decreased exponentially with its decline (Worm et al., 2006). This phenomenon may occur because the coastal zone and existing ecosystems have high biodiversity that offers a supply of environmental goods and services (Kaiser et al., 2005). Therefore, these ecosystems are more affected by the multiple, increasing anthropogenic activities in recent years (Halpern et al., 2015), which can sometimes have long-term irreversible effects.

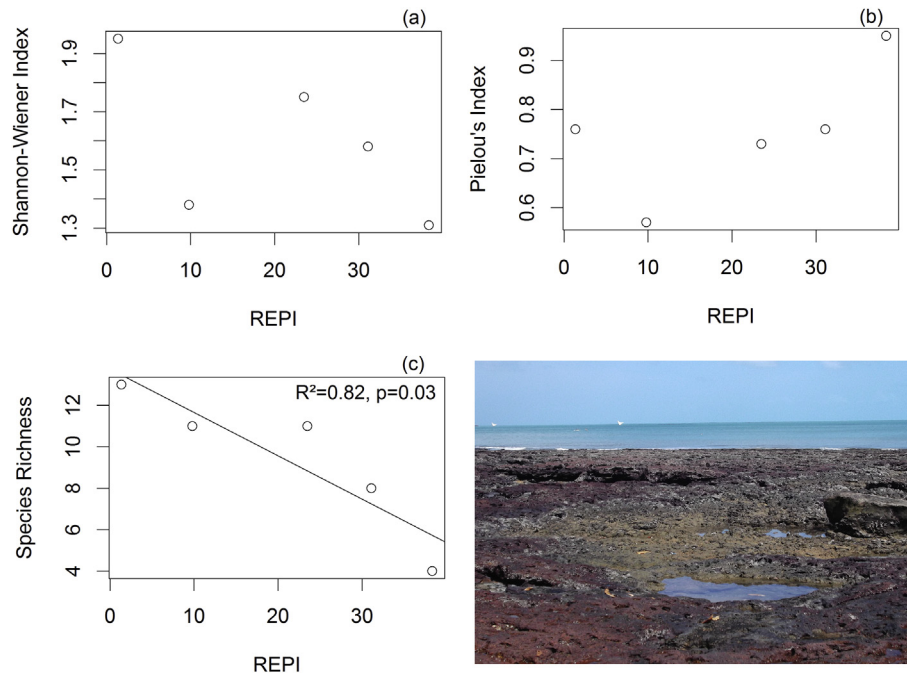
The REPI has a clear relationship with species loss. This index considers both the quantity and quality of anthropogenic pressure based on several indicators, although some of these indicators may be correlated. However, it is also important to assess the independent relationships of various anthropogenic pressures on species richness, since the actual force of each anthropogenic pressure on benthic communities varies according to their location. Separation of these pressures, which were previously grouped in a single index, allows for identification of the factors that most strongly affect benthic communities with greater or lesser intensity. Halpern et al. (2015) reported that little is known regarding the human stressors causing major changes in marine biodiversity for many regions. The results of the present study indicate that the percentage of urban areas, and the presence of storm sewers, beach kiosks, beachfront restaurants, fish markets, and jetties (structures developed for the control of coastal erosion) showed a negative relationship with species richness in these intertidal reefs. The use of the REPI allowed for an indirect evaluation of the effects of pollution, erosion, and siltation on the structure of sessile benthic communities.

The percentage of urban areas, storm sewers, beach kiosks and beachfront restaurants, and jetties could simultaneously explain the reduction of species. According to Vieira et al. (2011), storm sewers are local sources of fecal pollution on the beaches in the Fortaleza coastal zone, which are used for the flow of sewage through illegal connections. In many places, drainage systems are used for discharging waste from hotels, marinas, fish markets, beachfront restaurants, and beach kiosks, contributing to the increase in pollution in tourism-heavy cities with high population densities (Davenport and Davenport, 2006), such as Fortaleza. This hypothesis is corroborated by research conducted on the anthropogenic impacts in Fortaleza by Cavalcante et al. (2009, 2012), Buruaem et al. (2012), Nilin et al. (2013), and Almeida et al. (2016). These recent studies have shown that unplanned urbanization, a lack of sanitation, and demographic growth have caused losses of water quality through increased organic contaminants, heavy metals, and nutrients.

Increases in nutrients in the water supply decreases species richness by increasing the biomass of opportunistic species (Borowitzka, 1972; Díez et al., 1999; Tewari and Joshi, 1988); this phenomenon is spreading in coastal areas worldwide (McGlathery, 2001; Schaffelke et al., 2005). In this context, the ecological status of aquatic ecosystems has often been associated with differences in abundance between perennial and opportunistic species (Guinda

**Table 5**  
Tropical reefs, relative environmental pressure index (REPI), and their values and weights in Ceará west coast, Tropical Southwestern Atlantic.

Coastal reefs	Reef area (ha)	Urban development		Coastal structures					Fishing activity	REPI
		Urban area (ha)	Percentage of urban areas (%)	Beach kiosks and restaurants (N)	Jetties (N)	Fish markets (N)	Storm sewers (N)	Port ships (N)	Fishing sheds (N)	
1. Meireles	4.35	12,408.34	82.72	30	2	1	7	1	0	38.36
2. Dois Coqueiros	10.17	10,811.20	72.07	5	0	0	0	0	0	31.12
3. Pacheco	13.62	8201.63	54.67	0	0	0	0	0	1	23.48
4. Taíba	12.81	413.36	2.75	1	0	0	0	0	3	1.37
5. Paracuru	25.91	3279.40	21.86	1	0	0	0	1	5	9.80
Weight	–	–	9	1	3	1	3	3	1	–



**Fig. 4.** Relationship between the relative environmental pressure index (REPI) and (a) Shannon's diversity, (b) Pielou's evenness, and (c) Species richness on tropical reefs.

et al., 2008; Martins et al., 2012; Orfanidis et al., 2001, 2003; Scherner et al., 2013), and this difference has led to the loss of biodiversity (Scherner et al., 2013). In an increasing anthropogenic pressure gradient near Fortaleza, it is expected that the most sensitive species, generally the most specialized or k-selected species, would be gradually replaced by pollution-tolerant and indicator species, which are typically opportunistic or more r-selected species (Guinda et al., 2008). However, according to Ballesteros et al. (2007), we should also consider the effects of natural history and empirical evidence, because resistance to pollution cannot be explained only by the r-K selection theory (Pianka, 1970). Our results seem to support this assertion, because we observed the presence of perennial species in all reefs, and a high abundance of green macroalgae as biological indicators, even on the reefs with low REPI values.

According to Thornber et al. (2008), increases in the biomass of algae of the genus *Ulva* are good indicators of natural or anthropogenic additions of nitrogen to the water. In the Paracuru and Taíba reefs, which had the lowest percentage of urban areas and REPI values, we observed a higher percentage of area covered by the algae *Cladophora*, *Ulva fasciata*, and *U. lactuca*. Martins et al. (2012) reported that the presence or high abundance of *Ulva* spp. (see IndVal analysis) in preserved areas indicated that disturbances



caused by anthropogenic activities and changes in water quality may be occurring on a large scale. However, in the present study, algae belonging to the genus *Ulva* were not present in the Meireles reef, which had the highest percentage of urban areas and REPI values. Instead, we observed only two marine macroalgae, *C. acicularis* and *Pterocladia bartlettii*, in this tropical reef. The low richness indicates that this reef is under the influence of intense human pressure, including that caused by storm sewers (many of which are used for the flow of sewage through illegal connections).

Another important result is the relationship between jetties and species richness. Paula et al. (2013) showed changes in the coastal sediment balance in a sea-front region of Fortaleza due to engineering structures. Such changes lead to silting and erosion, both of which affect the benthic communities of reefs. Bezerra et al. (2007) emphasized that aspects of coastal dynamics were not evaluated in Mucuripe Harbor (Fortaleza city), and that the impacts were generated approximately 20–30 km west of this city, including the erosion/siltation of beaches, and consequently, of intertidal reefs. The construction of a jetty resulted in a change in sediment transport, which occurred naturally in the east–west direction and in the sheltered areas. Moreover, the current diffraction induced by the jetty caused siltation (Maia et al., 1998).

The results of the present study indicate the presence of a large

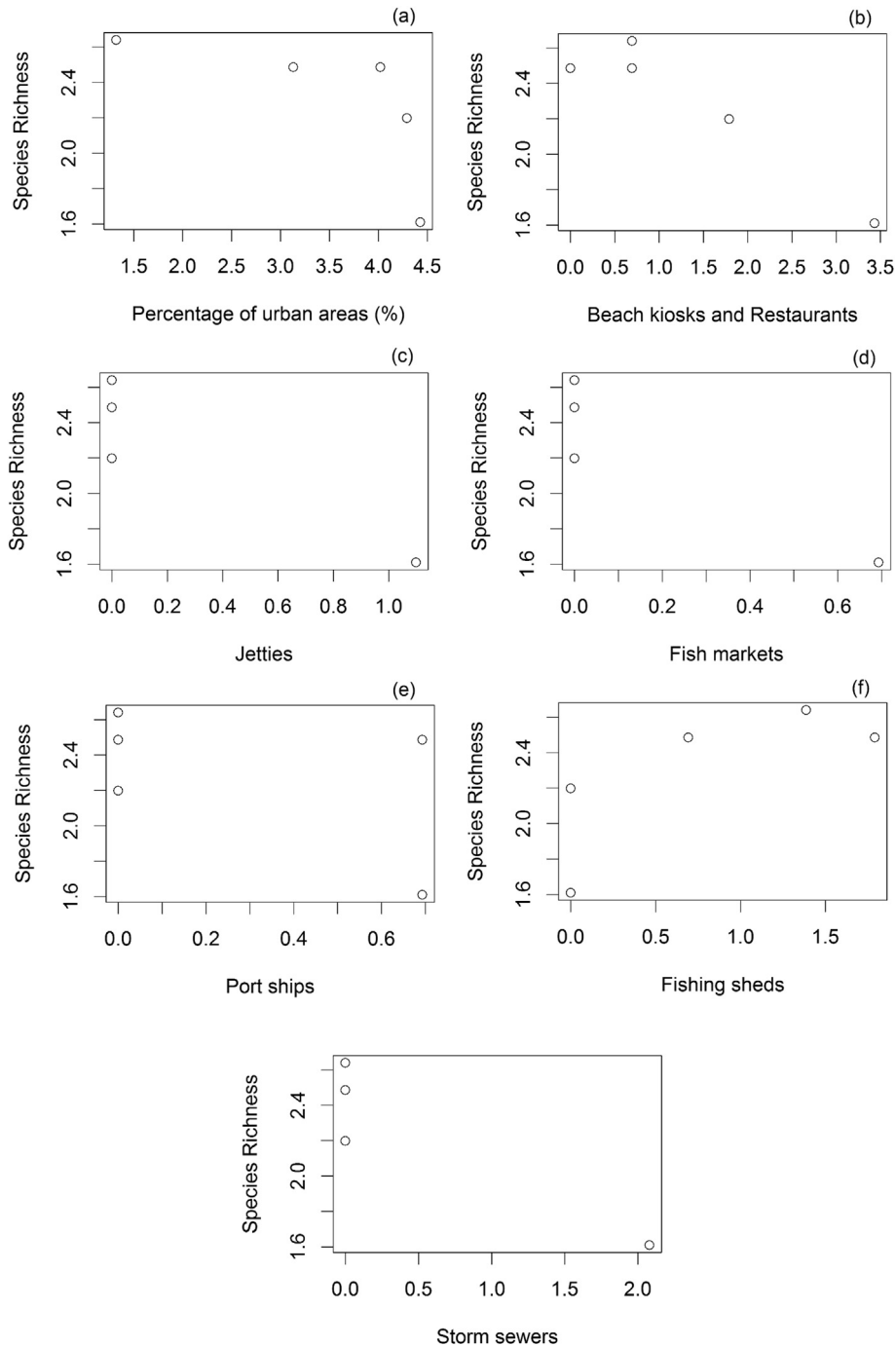


Fig. 5. Relationship between different anthropogenic pressures and species richness (data transformed using  $\log_e(x + 1)$ ).

quantity of sediment on these reefs, increasing in the westward direction. The reefs covered by fine and mobile sediments do not provide a solid and stable substrate for the establishment of algal spores, coral larvae, and juvenile stages of other sessile organisms (Furnas, 2003). Oigman-Pszczol et al. (2004) compared the presence of corals with the percentage of consolidated and unconsolidated substrate on rocky shores and found that the increased presence of empty space may be due to high sedimentation rates. In the Meireles and Dois Coqueiros reefs, the low percentage of sand on the reefs may have allowed for the establishment of the coral *S. stellata*, particularly in the low zones of the reef, due to the lower stress situation. Erfteimeijer et al. (2012) observed that sediment

deposition and suspended sediment affect reef community structure differently, selecting for adapted species such as the coral *S. stellata*. The coral *S. stellata* (a common species) is very resilient to sedimentation and other environmental factors, including temperature and turbidity, and is considered an indicator of anthropogenic stress in tropical reefs (Oigman-Pszczol et al., 2004). This species possesses large polyps (Menezes et al., 2014) that are less susceptible to the effect of sediments, and belongs to a genus known to be capable of actively removing sediments (Lirman and Manzello, 2009). However, coverage for longer periods (e.g., weeks or months) is lethal to virtually all species (Erfteimeijer et al., 2012; Lins de Barros and Pires, 2006). For example, the coastal reefs



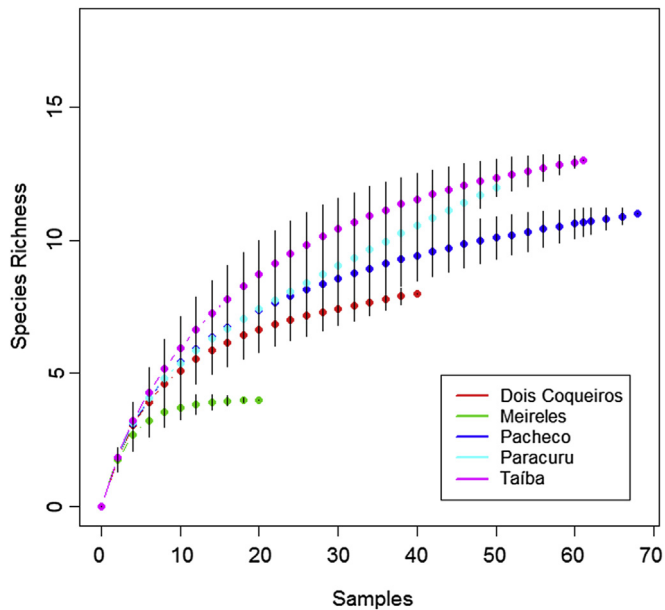


Fig. 6. Rarefaction curves of species richness in the tropical reefs (Ceará west coast, Tropical Southwestern Atlantic). Error bars indicate the 95% confidence intervals.

of Asia are experiencing widespread deterioration, largely as result of siltation caused by human disturbance (Fortes, 2001).

In the Paracuru reef, the greater presence of sand on the reef may have favored the development of *Sargassum* in the low zones. The large size of *Sargassum* reduces the probability of being covered by sediments. According to Lobban and Harrison (1994), the movement of water involves sedimentation, which is harmful to algae and other sessile organisms; however, some species are tolerant of sedimentation, and others have a competitive advantage in areas under sedimentation stress.

Despite their ecological and socio-economic relevance, scientific knowledge of benthic communities, intertidal variation, and anthropogenic pressure in tropical sandstone reefs is scarce. The few studies published on the Tropical Southwestern Atlantic coast were conducted on coralline algal or coral reefs (Francini Filho et al., 2013; Leão et al., 2003, 2010), whereas data on the benthic communities of intertidal sandstone reefs in the tropical coast are practically nonexistent. According to Murray et al. (1999), the association between the loss of species richness and pollution from the release of domestic and industrial effluents is well established in the literature. Nevertheless, the results presented herein have not been previously demonstrated in tropical reef ecosystems or considered in studies evaluating multiple anthropogenic pressures. Johnston and Roberts (2009) observed that the anthropogenic impact on benthic reef diversity has rarely been assessed, despite the recognition that reefs are subjected to a variety of anthropogenic pressures. Elucidating the factors that negatively influence the structure of the benthic community of these reefs is essential to better monitoring programs and prevent possible anthropogenic impacts on these environments.

## 5. Conclusions

Our study contributes new knowledge to the distribution patterns of benthic assemblages in this scarcely known region of the Tropical Southwestern Atlantic coast. We corroborate the hypothesis of Roberts et al. (2002), in that the areas of highest species richness such as tropical reefs are under the greatest threat from

anthropogenic activities. We emphasize that future studies on the multiple anthropogenic impacts to biological communities should use multiple indicators to identify the factors that have the largest impact on tropical marine biodiversity. The index (REPI) used in this work can be tested in many intertidal reefs as well as other environments worldwide, especially those in tropical areas.

It is important to monitor how tropical ecosystems respond to, and possibly adapt to, a changing environment when several factors are acting simultaneously. Therefore, more studies on the resilience of intertidal sandstone communities and the effects of anthropogenic pressures are needed for the management and adoption of conservation policies. The present results highlight the need for better infrastructure planning and rigorous monitoring, since the large influence of multiple human pressures in tropical reefs clearly leads to biodiversity losses.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.marenvres.2016.07.005>.

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