Regional Studies in Marine Science 48 (2021) 102014

Contents lists available at ScienceDirect

Regional Studies in Marine Science

journal homepage: www.elsevier.com/locate/rsma

Ecological health of coral reefs in Zanzibar

Henrique Bravo[a,b,c,*], Stefano Cannicci[b,d], Filip Huyghe[a], Martine Leermakers[e], Mohammed A. Sheikh[f], Marc Kochzius[a]

[a] Marine Biology, Ecology & Biodiversity, Vrije Universiteit Brussel (VUB), Pleinlaan 2, 1050 Brussels, Belgium
[b] The Swire Institute of Marine Science and Division for Ecology and Biodiversity, School of Biological Sciences, The University of Hong Kong, Hong Kong SAR, PR China
[c] Groningen Institute for Evolutionary Life Sciences, University of Groningen, PO Box 11103, 9700 CC, Groningen, The Netherlands
[d] Department of Biology, University of Florence, via Madonna del Piano 6, 50019, Sesto Fiorentino, Italy
[e] Analytical and Environmental Chemistry, Vrije Universiteit Brussel, Pleinlaan 2, 1050 Brussels, Belgium
[f] Tropical Research Center for Oceanography, Environment and Natural Resources (TROCEN), State University of Zanzibar, Tanzania

ARTICLE INFO

Article history:
Received 7 May 2021
Received in revised form 12 September 2021
Accepted 15 September 2021
Available online 20 September 2021

Keywords:
Bioindicator
Biomonitoring
Coral reefs
Indian Ocean
Tanzania
Trace metals

ABSTRACT

Coral reefs are important ecosystems in terms of their biodiversity and ecosystem functions. Particularly at local scales, coral reefs are vulnerable to natural and anthropogenic disturbances, leading to the degradation of reef health. Here, we employed two different methods to monitor reef health. First, we conducted line transect surveys to record the benthic community structure to infer ecological reef health. Secondly, trace metal concentrations in sediment samples and a bioindicator sponge species, *Haliclona fascigera*, were compared among sites to detect cryptic degradation and unknown sources of pollution. The study area comprised six reefs situated along the coast of Zanzibar's main agglomeration, Stone Town, and subject to different types of disturbances and conservation management schemes. Overall, coral reef health was found to decrease with increasing proximity to Stone Town, with living hard coral cover being particularly low on reefs closest to Stone Town, which coincided with greater fishing, tourism, and pollution pressures. Reef assessments based on trace metal analyses differed from the community structure surveys. All sites showed high levels of arsenic and cadmium contamination, with some samples revealing concerning levels of chromium, copper and zinc. The reefs differed significantly between each other in terms of trace metal concentration for both sediments ($p = 0.031$, PERMANOVA) and sponge samples ($p = 0.001$, PERMANOVA). Trace metal concentrations were not correlated with distance to Stone Town, highlighting the downstream effects of industrial and urban sewage on even remote reefs. Coral reef health assessment was found to be dependent on the survey method employed, which is why we recommend the combination of complementary methods.

1. Introduction

Coral reefs are marine habitats of critical ecological importance present in tropical and sub-tropical shallow coastal waters ranging between 25°S and 25°N (Hoegh-Guldberg, 1999). They can encompass thousands of species, making them one of the most diverse ecosystems in the marine environment (Paulay, 1997).

Coral reefs have also been identified as one of the ecosystems with the highest monetary value to humans (Costanza et al., 1997; Alongi, 2012). Over 450 million people from 109 different countries live in the vicinity of coral reef ecosystems (Pandolfi et al., 2011), with many communities benefiting directly from ecosystem services, such as shoreline protection, food supply, tourism, and extraction of materials (Burke et al., 2011).

The ecological balance in these complex systems is vulnerable to disturbances at local scales that can be due to biological interactions, such as competition or predation (Sammarco, 1980; McCook et al., 2001), or due to anthropogenic pressure (Hodgson, 1999), such as pollution (Thompson et al., 2004; Moynihan et al., 2012), fisheries (Jennings and Kaiser, 1998), intensive agriculture (Folke and Kautsky, 1992; Fabricius, 2005) and tourism (Mak and Moncur, 1995; Hall, 2001).

With so many threats, the effective conservation of coral reefs is of paramount importance. Their protection should ensure that the reef is able to retain its ecosystem functions, whilst providing some of its resources to humans. Finding a balance between these two factors is difficult and exploiting the ecosystem past the threshold point could eventually lead to an ecological collapse

---

[*] Corresponding author at: Groningen Institute for Evolutionary Life Sciences, University of Groningen, PO Box 11103, 9700 CC, Groningen, The Netherlands.
E-mail address: henrique.bravo@rug.nl (H. Bravo).

https://doi.org/10.1016/j.rsma.2021.102014

(Hardin, 1968; Hilderbrand et al., 2005; Marten, 2001). This has been observed on coral reefs that were unable to recover following a high disturbance event of either natural or anthropogenic nature (Rogers and Miller, 2006; Norström et al., 2009).

In order to evaluate the current state of a reef, several reef surveying techniques can be employed, depending on availability of resources, ease of access to sites or suitability for the scope of the project (Hill and Wilkinson, 2004). Different properties of the reef can be measured, and they usually fall within two categories: biological parameters and physical parameters. The biological ones tend to rely on simpler ecological surveys using transects and quadrats to infer the quality and quantity of substrate cover and the associated fauna, whereas to measure physical parameters more complex approaches or specialised equipment are usually required (Hill and Wilkinson, 2004). These can involve the use of stable isotopes (Heikoop et al., 2000; Moynihan et al., 2012), trace metal analyses of sediments or tissue samples of bioindicators (Guzmán and Jiménez, 1992; Rayment and Barry, 2000; Cooper et al., 2009), sedimentation traps (Storlazzi et al., 2011), hydrometer, refractometer, and secchi discs (English et al., 1997; Hill and Wilkinson, 2004).

Marine bioindicators can be a powerful tool in the monitoring of reefs, because they have the ability to provide early warning signals, in contrast to a benthic census that is only able to identify changes in present compared to past coral cover (Cairns and van der Schalie, 1980; Linton and Warner, 2003). Bioindicators can detect pollution and/or degradation in the environment and their use could help avoid further damages to the ecosystem (Rainbow and Phillips, 1993). A good marine bioindicator species should be sessile, filter-feeding, easily identifiable in the field, long-living, abundant, widely distributed, large and tolerant to physical and chemical oscillations (Rainbow and Phillips, 1993; Batista et al., 2014).

Marine sediments have also been reported to be an indicator of pollution mainly originating from dumping of solid and liquid waste, burning of diesel and sewage (Negri et al., 2006). They could provide another useful tool for the monitoring of cryptic degradation in reef ecosystems.

The main objective of this study was to assess the ecosystem health of several reefs along the western coastline of Zanzibar's main island, Unguja, by using a combination of different approaches. A traditional visual census survey investigating the benthic composition of the reefs was employed, as was the measurement of trace metals in a bioindicator species and in sediments located in the same reefs. The sponge *Haliclona fascigera* was the species chosen as a bioindicator due to possessing all of the characteristics of reliable bioindicator organisms and since there have been studies that used species of the same genus successfully (Rao et al., 2009; Aly et al., 2013).

Coral reefs in Zanzibar face several threats, such as overexploitation of coastal resources, poor land use practices resulting in sediment and nutrient run-off, tourism related activities, coral bleaching and pollution from land and maritime transport (Salm et al., 1998; McClanahan et al., 2000). Chemical and biological coastal pollution raises a serious concern regarding the health of marine ecosystems around Zanzibar, including coral reefs (Moynihan et al., 2012; Nyanda et al., 2016).

To date, most studies conducted in East Africa have focused on the potential effects of chemical pollutants on mangrove ecosystems (De Wolf and Rashid, 2008; Kruitwagen et al., 2008; Rumisha et al., 2012, 2017a,b), and while there is an apparent deterioration of coral reefs, only a limited number of studies have focused on the health of coral reef ecosystems around the island of Unguja (Lokrantz et al., 2010; Muzuka et al., 2010; Herrán et al., 2017).

We hypothesised that (a) there is a higher percentage of living hard coral cover at sites located farther away from Stone Town (largest city of Zanzibar archipelago) than those closest to it and (b) the levels of trace metals follow the trend of hard coral cover, with highest levels at sites closest to Stone Town.

2. Materials and methods

2.1. Study site

Six fringing reefs, out of the known approximately 10 reef patches, located next to small islands or sandbanks were chosen near the West coast of Unguja Island (Zanzibar, Tanzania) to carry out this study (Fig. 1). The reefs were chosen based on their distance to Stone Town (6°09′47.5″S, 39°11′08.4″E), because it is the most populated area of Unguja and where the port is also located. When possible the sites were sampled on the Northeast side of the island or sandbank. In order of farthest to closest, the selected study sites were the following: Chumbe (12.9 km: 6°16′42.7″S, 39°10′28.6″E), Nyange (11.3 km: 6°15′36.8″S, 39°07′44.9″E), Murogo (6.4 km: 6°11′05.3″S, 39°07′55.5″E), Bawe (5.9 km: 6°09′14.0″S, 39°07′58.3″E), Pange (4.5 km: 6°10′58.8″S, 39°08′59.4″E) and Chapwani (4.3 km: 6°07′32.9″S, 39°11′38.2″E) (Fig. 1).

2.2. Ecological surveys of benthic community structure

The surveys were conducted throughout a period of four weeks between February and March 2015, at low tide and whilst snorkelling. To assess the community structure of the six different sites, four replicate transects of 20 m each were selected parallel and close to the reef crest, on the reef flat at depths ranging from three to four metres at low tide. The method used was the Line Intercept Transect (LIT) (Loya, 1978; English et al., 1997), which consists of laying a 20 m tape in a random location and recording the length of each different type of substrate and organism beneath the tape to the nearest centimetre. Corals were identified to genus level: *Acropora* spp., *Fungia* spp., *Lobophyllia* spp., *Porites* spp. and *Turbinaria* spp. Other benthic sessile organisms (as well as sea urchins) and substrates were grouped into categories: algal cover, anemone, dead coral, dying *Acropora* spp., giant clam, mussel, rocky substrate, rubble, sand, sea urchin, sponge, and soft coral (Table 2). Sea urchin density was also measured for the different reefs (Table S1).

2.3. Trace metal sampling and analysis

Samples of sediments and of the bioindicator species *Haliclona fascigera* for trace metal analysis were collected randomly at high tide in the vicinity of the transects and during the same period as the ecological surveys, using SCUBA at a depth ranging from 7–12 m. Sediment samples were collected from a depth of 10 cm below the seafloor to avoid the surface layer. Bioindicator samples were collected from all sites, except for Chapwani, where *H. fascigera* was absent. After collection, the samples of both sediments and sponges were kept frozen at temperatures below −20 °C for a period of 7–12 days before being dried at 55 °C for a minimum of 48 h. Sediment and biological samples were ground with a pestle and mortar until fine grains were obtained. Three to four replicates were used per site.

Trace metals were analysed following the method by Rumisha et al. (2012). Approximately 0.2 g of each sample was weighed and placed in Teflon vessels for digestion with the CEM Mars 5 microwave. For the digestion of sediments, 6 ml of highly purified concentrated hydrochloric acid (HCl; 30%) and 2 ml of nitric acid (HNO_3; 65%) were added to the vessels and placed in the microwave. The samples were digested at 180 °C (ramp time 15 min and hold time 15 min) and 200 psi of maximum

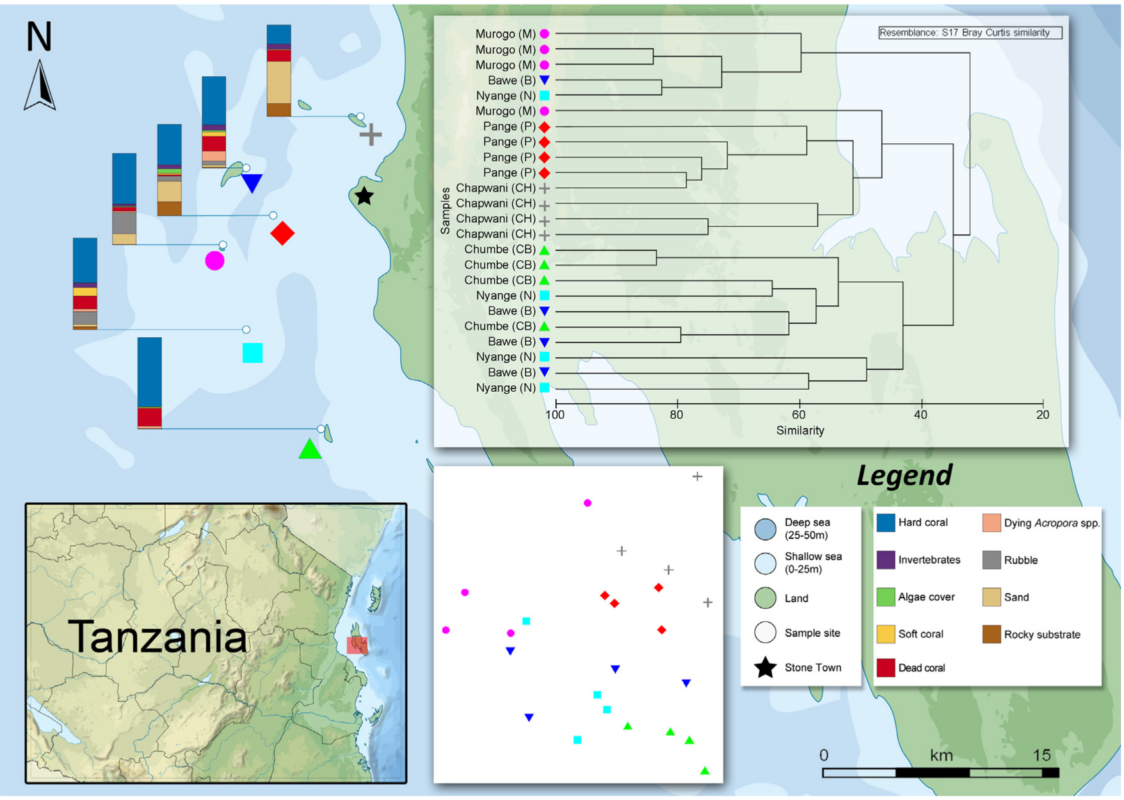

Fig. 1. Location of the study sites in Zanzibar off the west coast of Unguja island. Stacked bars represent the percentage of each benthic category at each site. Dendrogram and multi-dimensional scaling (MDS) plots depict the similarity between the replicates at the different sites.

pressure, and then left to cool down. A similar procedure was followed for the digestion of the sample of the bioindicator, where 5 ml of highly purified concentrated nitric acid (HNO_3; 65%) and 1 ml hydrogen peroxide (H_2O_2; 30%) were added to 0.2 g of the sample in the Teflon vessel. After digestion, 40 ml of deionised water was added to the samples and the samples were transferred to polyethylene (PE) bottles. After all samples had been processed, these were diluted once more with deionised water before analysis (dilution factor 10) and placed in test tubes for the concentration of trace metals to be measured with a High Resolution Inductively Coupled Plasma Mass Spectrometer (HR-ICP-MS) (Element II; Thermo Fisher Scientific, Bremen, Germany). Each digestion set contained at least one blank and one certified reference material (CRM). Dogfish (*Squalus acanthias*) liver DOLT-3 (National Research Council, Canada) and River clay sediment LGC 6139 (Laboratory of the Government Chemist, United Kingdom) were used as CRM. The results from the controls and reference materials confirmed that the measurements were reliable. Recoveries for all elements (Aluminium (Al), Arsenic (As), Cadmium (Cd), Cobalt (Co), Chromium (Cr), Copper (Cu), Iron (Fe), Manganese (Mn), Nickel (Ni), Lead (Pb), Vanadium (V) and Zinc (Zn)) were within 10% of the certified values. Precision, determined as the percentage coefficient of variation, for replicate analysis of the CRM ranged from 1 to 10%.

2.4. Data analyses

Similarity between sites and transects of each site were visualised through a non-metric multi-dimensional scaling (MDS) plot and hierarchical cluster analysis (Fig. 1). Differences in community structure, trace metals in sediment and bioaccumulation were analysed using multivariate methods. The original data matrix was log transformed, after a preliminary PERMDISP test using medians, the equivalent of a Levene's test (Anderson et al., 2008), found significant heterogeneity of variances within the tested groups.

A one-way permutational multivariate analysis of variance (PERMANOVA) was carried out to test for differences in community structure, Enrichment Factor (EF) and Biota-Sediment Accumulation Factor (BSAF) across sites. All analyses were performed using PRIMER (version 7.0.13; Plymouth Routines In Multivariate Ecological Research; PRIMER-E Ltd.; Clarke and Warwick, 2001).

The EF of trace metals was calculated for sediment samples, and the BSAF was estimated for the bioindicator samples. The EF determines whether the levels of trace metals present in the sediments are from natural or anthropogenic sources Eq. (1). This was done by calculating the ratio of a chosen metal and the concentration of aluminium (Al) in a given sample. The ratio between a given trace metal and the concentration of Al in the background was also estimated. This was achieved by using the concentration values of the trace metals in the upper Earth's crust (Wedepohl, 1995). The EF was finally obtained by calculating the ratio between the two previously described ratios. This is demonstrated with the following equation:

$$EF = \frac{\frac{CM}{CAl}\,(\text{sample})}{\frac{CM}{CAl}(\text{background})} \qquad (1)$$

The results obtained were compared with the different categories of EF already established in the literature (Table 1) (Sutherland, 2000; Yongming et al., 2006).

The BSAF allowed inferring whether an organism is accumulating trace metals based on the concentration of these metals in the sediments collected from the same site Eq. (2). BSAF was estimated with the ratio between the concentration of trace metals in the bioindicator and the concentration of the same trace metal in the sediments. Results above the value of 1.0 are usually considered to represent bioaccumulation of trace metals in the

Table 1
Enrichment categories based on Enrichment Factor (EF) values.

EF	Category
<2	Depletion to minimal enrichment
2–5	Moderate enrichment
5–20	Significant enrichment
20–40	Very highly enriched
>40	Extremely enriched

bioindicator (Rumisha et al., 2012). In the following equation CM represents the concentration of the chosen metal:

$$\mathrm{BSAF} = \frac{CM\ (\text{Tissue})}{CM(\text{Sediments})} \tag{2}$$

A nonlinear asymptotic model was also conducted in order to infer the interaction between community structure and distance from Stone Town. The model was calculated using the following equation:

$$P = C - ke^{-qD} \tag{3}$$

where P stands for the percentage of hard coral, C the asymptotic hard coral cover, k the linear coefficient of coral reef shrinking due to proximity to Stone Town, q the exponential rate of shrinking and D the distance to Stone Town.

Further regressions were carried out to test the relationship between trace metal levels in sediments and bioindicator in relation to distance from Stone Town and from shore. All analyses were computed with R software (R Core Team, 2019) using the following packages: ggplot2 (Wickham, 2016), ggpubr (Kassambara, 2020), minpack.lm (Elzhov et al., 2010), RColorBrewer (Neuwirth, 2014) and vegan (Oksanen et al., 2020).

3. Results

3.1. Community structure

The nonlinear asymptotic model showed a clear positive trend between hard coral cover and distance from Stone Town until it reaches a plateau of 59.2% of hard coral cover (Fig. 2). Hard coral cover was the only statistically significant parameter to be determined ($p < 0.001$; Table S2). Chapwani was characterised by the lowest hard coral cover, displaying an average of 20.8% of hard coral out of the total benthic cover and Chumbe by the highest at 75.5% of its benthic cover being hard coral (Table 2). Whilst most sites depicted a steady increase in hard coral cover as distance increased, Murogo showed disparities with some parts of its reef reaching values as high as those of Chumbe (89.5%) and some as low as in Chapwani (11%). The patterns of benthic cover significantly varied among the six different sites (pseudo-F = 5.21, df = 5, p = 0.001, PERMANOVA test). A significant difference was detected for 12 out of the 15 pairwise comparisons ($p < 0.05$, PERMANOVA post-hoc test). Only the following comparisons proved to be not significantly different: Bawe vs Nyange, Bawe vs Murogo, and Nyange vs Murogo. The substrate categories mostly responsible for the above significant differences amongst sites were *Fungia* spp. corals, *Acropora* spp. corals, dead coral (abundant in Chumbe and Bawe), rubble (dominating in Murogo and Nyange) and sand and rocky substrate, which dominated Pange (15.3% and 22.6%, respectively) and Chapwani (14.3% and 46%, respectively). The latter two were the poorest sites in terms of abundance of hard coral and were also the closest sites to Stone Town (Figs. 1 and 2; Table 2). Nyange and Bawe displayed very similar benthic cover results, particularly for the following categories: sea urchins (4.9% and 4.4%, respectively), *Acropora* spp. corals (23.3% and 23.6%, respectively), and dead coral (14.1% and 16 %, respectively).

3.2. Trace metal analyses

3.2.1. Sediments

The average concentration of trace metals in sediments shows a high concentration of most metals for Chumbe and Murogo, when compared to the other sites (Table 3). However, the calculation of enrichment factors for the different metals revealed some other underlying patterns, particularly that As, Cd, and Cr, showed signs of high enrichment in sediments across all sites (EF > 5; Table 4). Conversely, other trace metals showed values that suggested no enrichment had taken place, such as Co, Fe and Mn (EF < 2; Table 4). Enrichment levels differed significantly among sites (pseudo-F = 1.62, df = 5, p = 0.031, PERMANOVA test), although post-hoc tests revealed that only the comparisons between Pange vs Chumbe, Pange vs Bawe and Pange vs Murogo were statistically significant ($p < 0.05$, PERMANOVA post-hoc test).

3.2.2. Bioindicator

The average concentration of trace metals in the bioindicator shows again high concentration of many trace metals for Chumbe when compared to the other sites (Table 5). The further calculation of the BSAF for the different trace metals revealed that As, Cd, Cu, and Zn were bioaccumulated by the bioindicator across all

Table 2
Mean (±SE) per cent contribution of the different substrate types to the total benthic cover at each reef, obtained from 20 m transects. *Algae cover comprises turf algae and crustose coralline algae. **Sea urchin density at the different sites can be found in Table S1.

Substrate type (%)	Chapwani	Pange	Bawe	Murogo	Nyange	Chumbe
Acropora spp.	13 (±1.7)	30 (±3.7)	23.6 (±5.3)	6.5 (±0.9)	23.3 (±5.6)	62.6 (±7.3)
Fungia spp.	0	0	0.5 (±0.4)	0.4 (±0.2)	1.8 (±1.2)	0.1 (±0.1)
Lobophyllia spp.	0	0.5 (±0.5)	0	0	0	0.3 (±0.3)
Porites spp.	7.8 (±4.1)	13.9 (±4.4)	27.8 (±8.6)	48.6 (±17.3)	18.5 (±13)	9.9 (±4.9)
Turbinaria spp.	0	0	1 (±1)	0	5.5 (±4.9)	2.6 (±2.6)
Algae cover*	0	4.9 (±1.9)	1.8 (±1.6)	1 (±0.7)	0	0.9 (±0.5)
Anemone	0.4 (±0.4)	0.5 (±0.5)	1.6 (±0.7)	0.4 (±0.4)	0.1 (±0.1)	0
Clam	0.1 (±0.1)	0	0	0	0	0.1 (±0.1)
Mussel	0	0.1 (±0.1)	0	0	0	0
Sea urchin**	5.3 (±0.5)	3.4 (±2)	4.4 (±1.3)	2 (±1.4)	4.9 (±1.4)	0
Sponge	0	0.4 (±0.2)	0	0	0	0
Soft coral (*Sarcophyton* spp.)	0.9 (±0.5)	1.6 (±1.1)	4.9 (±4.2)	0	9.5 (±4.9)	0.9 (±0.6)
Dead coral	12.4 (±7.9)	1.3 (±0.8)	16 (±6.1)	4.4 (±2.5)	14.1 (±8)	19.5 (±7.6)
Dying *Acropora* spp.	0	0	11 (±6.4)	1.3 (±0.8)	3 (±2)	2.9 (±2.9)
Rubble	0	5.6 (±1.8)	4.4 (±4)	23.4 (±8.4)	13.8 (±2.8)	0
Sand	46 (±10.3)	22.6 (±3.1)	2.5 (±1.2)	11.9 (±7.9)	2.5 (±1.9)	0.1 (±0.1)
Rocky substrate	14.3 (±6.6)	15.3 (±6.3)	0.6 (±0.6)	0.3 (±0.3)	3.1 (±2.8)	0.1 (±0.1)

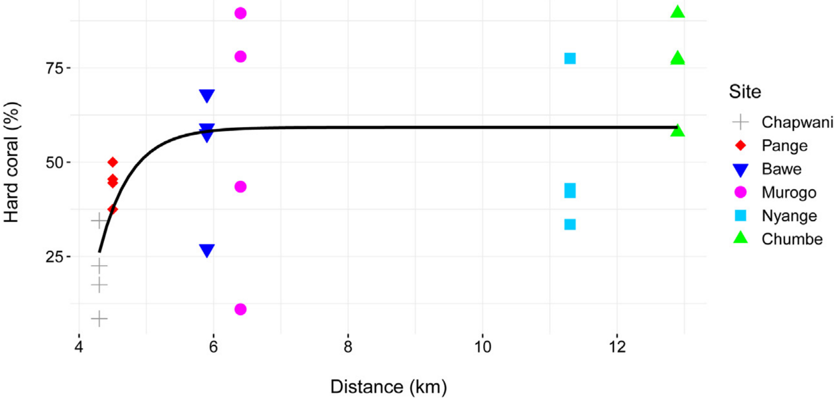

Fig. 2. Percentage of hard coral as a function of distance from Stone Town. Black line depicts the non-linear asymptotic model line.

Table 3
Average concentration (µl/g dry weight) of trace metals in coral reef sediments across the west coast of Unguja Island (Zanzibar, Tanzania).

Site	Al	As	Cd	Co	Cr	Cu	Fe	Mn	Ni	Pb	V	Zn
Chumbe	2055.1	0.7	0.1	0.3	0.7	6.8	1210.6	16.8	2.0	0.7	3.0	3.1
Nyange	489.4	0.6	0.1	0.1	2.1	2.2	322.1	4.8	0.7	0.7	1.0	3.9
Bawe	729.3	0.5	0.0	0.1	0.4	2.6	418.5	6.4	0.7	0.4	1.2	1.0
Pange	377.0	0.6	0.0	0.1	0.1	2.5	209.7	5.0	0.5	0.3	1.0	0.7
Murogo	1142.7	0.6	0.1	0.2	0.3	3.9	700.3	15.4	1.6	0.4	1.8	1.7
Chapwani	704.4	0.9	0.0	0.1	0.3	2.8	460.1	7.0	0.9	0.5	1.3	1.8

Table 4
Sediment enrichment factor for trace metals normalised by Al for coral reef samples at Unguja Island (Zanzibar, Tanzania).

Site	As	Cd	Co	Cr	Cu	Fe	Mn	Ni	Pb	V	Zn
Chumbe	14.0 *	22.2 **	1.1	0.8	17.9 *	1.5	1.2	4.1	1.6	2.1	2.2
Nyange	45.9 ***	87.9 ***	1.0	9.7 *	24.5 **	1.7	1.4	6.1 *	6.9 *	2.8	12.0 *
Bawe	23.9 **	27.8 **	1.1	1.2	19.3 *	1.4	1.3	4.1	2.4	2.3	2.0
Pange	59.2 ***	60.4 ***	1.1	0.7	35.8 **	1.4	1.9	5.4 *	3.4	3.9	2.6
Murogo	19.1 *	37.6 **	1.1	0.7	18.4 *	1.5	2.0	5.8 *	1.7	2.4	2.2
Chapwani	47.8 ***	32.3 **	0.9	0.9	21.9 **	1.6	1.5	5.3 *	3.1	2.7	3.8

* Significant enrichment.
** Very high enrichment.
*** Extremely high enrichment.

Table 5
Average concentration (µl/g dry weight) of trace metals in *Haliclona fascigera* (bioindicator) across the west coast of Unguja Island (Zanzibar, Tanzania).

Site	Al	As	Cd	Co	Cr	Cu	Fe	Mn	Ni	Pb	V	Zn
Chumbe	130.0	4.3	3.2	0.1	3.8	0.4	124.8	1.6	0.9	0.5	0.2	45.7
Nyange	695.9	1.8	1.6	0.3	3.1	0.8	117.9	1.7	2.6	1.7	0.4	33.4
Bawe	222.9	2.7	2.6	0.1	2.5	0.5	102.4	1.9	1.1	0.9	0.3	29.6
Pange	241.1	2.0	1.3	0.3	2.7	0.8	128.0	1.7	0.9	2.2	0.4	46.1
Murogo	435.9	3.0	2.5	0.2	3.1	0.8	130.5	1.4	1.2	1.8	0.4	38.6

sites (BSAF > 1; Table 6). Other trace metals, such as Co, Ni and Pb, also revealed a high degree of bioaccumulation for all sites with the exception of Chumbe and Murogo for Ni. Metals such as Al, Cr, Fe, Mn and V showed no or very little signs of bioaccumulation across all sites (BSAF < 1; Table 6).

Further statistical analyses showed that the levels of trace metals present in the bioindicator differed significantly among the sites (pseudo-F = 21.28, df = 5, p = 0.001, PERMANOVA test), with post-hoc tests revealing that all comparisons were significant ($p < 0.05$, PERMANOVA post-hoc test), with the exception of Bawe vs Murogo.

Table 6
Biota-sediment bioaccumulation factor (BSAF) for trace metals for *Haliclona fascigera* (bioindicator) samples at Unguja Island (Zanzibar, Tanzania).

Site	Al	As	Cd	Co	Cr	Cu	Fe	Mn	Ni	Pb	V	Zn
Chumbe	0.1	5.8 *	54.1 *	0.4	5.4 *	0.1	0.1	0.1	0.5	0.7	0.1	14.8 *
Nyange	1.4 *	3.1 *	28.0 *	3.5 *	1.5 *	0.4	0.4	0.4	3.7 *	2.3 *	0.4	8.5 *
Bawe	0.3	6.1 *	98.0 *	1.2 *	6.2 *	0.2	0.2	0.3	1.6 *	2.4 *	0.2	30.2 *
Pange	0.6	3.5 *	44.1 *	4.6 *	21.4 *	0.3	0.6	0.3	1.9 *	7.8 *	0.4	68.8 *
Murogo	0.4	5.4 *	44.2 *	1.1 *	9.0 *	0.2	0.2	0.1	0.8	4.3 *	0.2	22.6 *

* Bioaccumulation.

3.3. *Relationship*

There was no clear trend observed between the levels of trace metals present in sediments (EF) and in the bioindicator (BSAF), with the levels increasing linearly in both factors for some of the trace metals, particularly Cd, as well as Zn, and As to a lesser extent.

Conversely, there were no significant relationships between BSAF and distance from Stone Town, BSAF and distance from shore, EF and distance from Stone Town or EF and distance from shore.

4. Discussion

4.1. *Community structure*

Coral reefs in Zanzibar provide a major economic benefit to local populations (Lange and Jiddawi, 2009) and the degradation of this fragile ecosystem could have serious implications not only for the environment, but also for the livelihoods of people that depend on it for sustenance (Staehr et al., 2018).

The present study showed that the reefs in question have a clear quality gradient on the west coast of Unguja island, with hard coral cover decreasing as proximity to Stone Town increases (Fig. 2), confirming the initial hypothesis, thus suggesting human impact as the most likely explanation for such pattern. The results of the benthic composition survey revealed similar trends to studies already conducted in the area (Lokrantz et al., 2010; Muzuka et al., 2010; Herrán et al., 2017) and was able to add baseline information for a new reef site (Murogo).

The higher hard coral cover at Chumbe, when compared to other sites, was to be expected because of its status as a Marine Protected Area (MPA; McClanahan et al., 1999) and the conservation practices enforced there (Nordlund et al., 2013). The high percentage of dead or dying *Acropora* spp. in this reef area are, however, slightly concerning. The absence of rubble or algal growth suggests that this was a recent event, also corroborated by results from previous studies where the percentage of dead or dying coral was considerably lower than those found here (Lokrantz et al., 2010; Muzuka et al., 2010). This could have been the result of the 2014 bleaching event (Eakin et al., 2019). *Acropora* spp. are known to be less resistant to coral bleaching (Baird and Marshall, 2002) and the *Acropora* colonies at Chumbe have been heavily impacted in the past by some of these events (Mohammed et al., 2000; McClanahan et al., 2007). With Chumbe having some of the highest percentage cover of *Acropora* spp. out of all the studied reefs (Fig. 2), this would be one of the sites most affected by bleaching and hence why the percentage of dying corals were lower in most other reefs. Chapwani, the closest site to Stone Town in this study, had the poorest benthic cover out of all surveyed sites. The scarce presence of hard coral was interspersed with large areas of sand, rocky substrate and sea urchins, suggesting an advanced state of reef degradation (Norström et al., 2009). Chapwani is a popular reef for snorkelling and fishing trips, because of its proximity to Stone Town. There is regular boat traffic as well as some destructive fishing taking place here (i.e. dynamite fishing in the past, and seine netting, drag netting and basket fishing currently), potentially adding to sediment resuspension and reef degradation (Johnstone et al., 1998; Lokrantz et al., 2010; Herrán et al., 2017). Pange, being the second site closest to Stone Town and located almost at the same distance as Chapwani, is also targeted by tourism and fishing, which are the two main sources of income for local communities that depend on marine ecosystem services for sustenance (Lange and Jiddawi, 2009). Bawe is located slightly farther away and perhaps showed an increase in coral cover because of that. However, because of the intense, but mostly artisanal, fishing pressure that occurs in these localities the sites are missing many fish species, particularly large herbivores and predatory species (Lokrantz et al., 2010). Without the presence of these species, an increase in either the algal growth or sea urchin density is expected, and consequently, a decline in hard coral cover, which can already be observed in Bawe, due to either a macroalgal dominance or high levels of bioerosion leading to a macroalgae dominated community or sea urchin barren state (Bellwood et al., 2004; Norström et al., 2009; Lokrantz et al., 2010). As the tourism business in Zanzibar grows, Bawe is also starting to see an increase in number of visitors in recent years. Murogo and Nyange are located farther away and are therefore less exposed to fishing or tourism pressure. The fishing pressure of Nyange has been reported as less than half of that of Pange or Bawe (Lokrantz et al., 2010). The type of fishing that occurs in Nyange and in areas outside of Chumbe is also less destructive than what occurs in those sites closest to Stone Town (Lokrantz et al., 2010), resorting more to hand lines and traps instead of gill nets or beach seine nets, potentially also influencing the coral cover and its associated fauna.

With a joint average hard coral cover of 49.6%, the sites covered in this study are slightly above the reported average for Tanzania (∼45%) and considerably above the mean for nine countries (30%) across the Western Indian Ocean (WIO) for which there is data available. In most Eastern African countries, coral cover has either declined over the years or has remained stable, mostly as a consequence of climate change and lack of conservation practices (Obura et al., 2017). Whilst the results found in hard coral cover in this study are encouraging, they also serve to highlight that reefs that are exposed to bigger anthropogenic pressures (e.g. fishing, even if artisanal; coastal development; coastal erosion; heavy transport use, tourism) such as Chapwani and Pange, are still at risk of degradation and collapse, as observed in other locations across the WIO (Obura et al., 2017).

4.2. Trace metals

Analyses on the levels of trace metals revealed high levels of both enrichment and bioaccumulation particularly for As and Cd across all sites, suggesting that these are of anthropogenic source, and the affected sites are polluted to a certain degree. The source for enrichment and bioaccumulation for these metals could be the same, but the lack of an apparent relation suggests there are other unknown factors at play. In addition, there were also high levels of Cr across all sediment samples and Cu and Zn for all bioindicator samples.

Whilst there was no clear trend of sites being more affected because of their proximity to Stone Town, the results matched those found in studies that took place in other coastal ecosystems around Zanzibar and in Dar es Salaam (Rumisha et al., 2012; Pant, 2013), where most sites also had signs of enrichment from As and Cd. These sites can be suffering from the impact of industrial or domestic discharges and fertiliser runoff from nearby fields (Rumisha et al., 2017b). In addition, the minimal sewage system has been shown to directly contribute to the enrichment of trace metals in both the water and reefs close to the island's shore (Moynihan et al., 2012). This suggests that the deterioration of reefs is not a consequence of the levels of trace metals found and that other anthropogenic factors must be playing a role in coral reef deterioration.

Since these reefs are located at comparable distances to Unguja's coastline, there is also no clear pattern when looking at distance to shore as a variable to explain the differences in EF or BSAF found in the studied sites. The proximity to major cities from mainland Tanzania (e.g. Dar es Salaam, Bagamoyo) could be a factor at play. The strong currents from the Zanzibar channel that during certain periods of the year have a predominantly northwards direction (Harvey, 1977), potentially bringing pollutants from the busiest port city in Tanzania and in sub-Saharan Africa, Dar es Salaam (Hönke and Cuesta-Fernandez, 2017), could be another factor. The maritime route used by ferries and transport ships connecting Stone Town to Dar es Salaam goes past Nyange, Pange and Chumbe and could potentially have an impact on the levels of trace metals being accumulated in sediments or in filter feeding species. This could be particularly impactful if the marine vessels release ballast waters in those areas as ballast waters have been reported to have increased levels of Cu and Cd that can change the chemical quality of marine environments (Dobaradaran et al., 2018).

Whilst most values of trace metals found in the reefs were relatively low compared to those found in the literature for similar areas (Muzuka, 2007; Sheikh et al., 2007; Rumisha et al., 2012; Pant, 2013), it is still worth noting that the absolute values of Cd in sediments are higher than those found on the coast of Dar es Salaam (Rumisha et al., 2012). The same is true for values of As that were higher than in the port of Dar es Salaam (Muzuka, 2007), two areas that would be expected to have higher values than the reefs in Zanzibar.

When looking at BSAF in other filter feeding species our results were also higher for many of the trace metals (e.g. As, Cd, Pb and Zn) (Rumisha et al., 2012, 2017b). It has been shown that some species of sponges require some trace metals (e.g. Zn) in high quantities in order to catalyse chemical reactions (Melawaty et al., 2014), but the difference in values across the sites suggests that there is clear bioaccumulation of harmful trace metals since these cannot be completely attributed to the requirements of the bioindicator. This could be concerning because the species reported in other studies are being caught for consumption, whilst the bioindicator species reported in this study will be consumed by herbivore fish species, which in turn will be consumed by humans or other fish (Dunlap and Pawlik, 1996; Bosch et al., 2015; Wulff, 2017). This accumulation of trace metals across the food web (Bri et al., 2018) can be detrimental to human health, as it has been shown from the consumption of other fish species at the top of the food web (e.g. tunas) (Storelli et al., 2010; Bosch et al., 2015). In this study, we found that the levels of Cd and Pb in the bioindicator species are considerably above the maximum allowed levels for human consumption (EC, 2011; PRC, 2012). Future work should focus on the levels of trace metals present in the different fish species consumed in Zanzibar to assess whether those levels are also of concern to human health.

4.3. Management and conservation

Many households in Tanzania depend directly on the exploitation of marine resources (Silva, 2006). There are over 43,000 fishermen in Tanzania, with 23,000 of them living in the Zanzibar Archipelago (Jiddawi and Ohman, 2002), making fishing an activity of utmost importance in Zanzibar (Silva, 2006; Lange and Jiddawi, 2009), and deeming it necessary to have constant measurements of fish stocks and pollution levels in sites where fish are consistently caught.

Coral reefs located in the vicinity of Stone Town, as seen in this study, are being more heavily impacted by anthropogenic pressure resulting in decreased coral cover and less abundance of fish (Lokrantz et al., 2010). Conversely, Chumbe, which is the farthest site to Stone Town and is to date the only strict no-take zone in Zanzibar, has the highest percentage of coral cover found in the present study and other studies conducted in the area (Herrán et al., 2017). Chumbe is home to nearly 90% of coral reef species found in East Africa and over 400 fish species (Nordlund et al., 2013), suggesting that nearby reefs could reach similar levels with appropriate conservation strategies.

If restoration projects or MPAs were to be implemented in any of the studied sites, Bawe and Nyange would be good candidates, alongside Murogo, as they do not display high levels of deterioration. These three sites have in fact been suggested as good potential Marine Conservation Areas (MCAs) in 2005 and 2012 (Ruitenbeek et al., 2005; McLean et al., 2012), but their status, to the authors' knowledge, has not yet changed.

Fishing frequency and methods should be managed carefully in order not to overexploit the current available resources, but also to maintain the livelihoods of people who depend on them. Quotas for both the amounts of fish allowed to be caught and for the fishermen permitted to be involved should be considered to ensure a sustainable practice. The studied reefs are devoid of large fish, including Chumbe, revealing an overfishing pressure (Lokrantz et al., 2010), and as aforementioned, the absence of certain species can negatively impact the reef because of the lack of herbivorous species to help avoid algal overgrowth or the spread of sea urchins for example. The same is true for marine recreational tourism, where big numbers of tourists could prove harmful due to the unawareness and unintended damaging impacts people can have on coral reefs (Barker and Roberts, 2004; Gil et al., 2015). Whilst the impacts are considered to be less than that of fishing, people can still damage corals or pollute the environment (Hall, 2001; Wilson and Verlis, 2017).

Sewage treatment in Zanzibar remains minimal and due to its recent high growth in both population and area, the areas adjacent to the city are expected to be the most impacted by pollution (Moynihan et al., 2012; Nyanda et al., 2016), putting at risk the local biodiversity as well as consumers of fish and seafood caught in such places. Since there was no clear trend of trace metal pollution, with similar values across all sites, the sources of this enrichment and bioaccumulation have to be looked into further before commercially exploited species start showing higher levels of bioaccumulation that could prove harmful to humans.

5. Conclusions

The quality of reefs along Unguja's west coast was found to be related to the distance of these reefs to Stone Town, the main agglomeration of people on Unguja Island. This correlation indicated that human impact was the most likely cause for the degradation of reefs, but the lack of a pattern in the trace metal analyses enables us to rule out this as a possible factor for reef deterioration found on reefs close to Stone Town. Other anthropogenic impacts such as fishing pressure, tourism or other contaminants could be related to the reef degradation that was observed, highlighting the need for further studies. The reports on the resurfacing of dynamite fishing and other destructive fishing is also a reason for concern and should be monitored (Obura et al., 2017).

Levels of As and Cd were present however in high levels in all sites for both sediment and bioindicator samples, reflecting a potential impact from industrial and domestic discharges directly into the water column. The bioaccumulation levels for Cd and Pb were also above the maximum allowed levels for human consumption so further work looking into other bioindicators, to corroborate these findings, and commercially caught fish species should be carried out.

Three further MCAs have been proposed around Zanzibar (McLean et al., 2012), including one that covers Pange, Bawe and Murogo. It is expected that there will be an increase in fish abundance and biomass and stricter tourism regulations, but the effectiveness of these newly proposed areas will have to be further investigated. It is worth noting that the status of MCA does not confer a physical barrier to threats in the water column. Management plans for these conservation areas that consider environmental parameters, and the mitigation of trace metals and other types of pollution, should be given priority.

CRediT authorship contribution statement

Henrique Bravo: Conceived and designed the study, Collected the samples and conducted the field work, Performed laboratory analyses, Analysed the data, Writing – original draft. **Stefano Cannicci:** Analysed the data, Writing – original draft. **Filip Huyghe:** Collected the samples and conducted the field work, Contributed (additions/corrections) to the manuscript. **Martine Leermakers:** Performed laboratory analyses, Contributed (additions/corrections) to the manuscript. **Mohammed A. Sheikh:** Performed laboratory analyses, Contributed (additions/corrections) to the manuscript. **Marc Kochzius:** Conceived and designed the study, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We would like to thank the institutions that have made our study possible: Erasmus Mundus, Belgium Masters Course "TROPIMUNDO" for granting a master thesis scholarship to HB; Vlaamse Interuniversitaire Raad - University Development Cooperation (VLIR-UOS), Belgium for providing a PhD scholarship to FH; VLIR-UOS for providing a travel grant to MK; the competent authorities in Tanzania for permits; Chumbe National Park for allowing the collection of data and their collaboration in the research project.

We are also indebted to the valuable comments by Dr. Anna Schleimer and Dr. Isis Guibert that helped improve this manuscript and to Bart Morent whose help in the field was invaluable. We further acknowledge the helpful and useful feedback from three anonymous reviewers that significantly bettered the manuscript.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.rsma.2021.102014.

References

Alongi, D.M., 2012. Carbon sequestration in mangrove forests. Carbon Manag. 3, 313–322. http://dx.doi.org/10.4155/cmt.12.20.

Aly, W., Williams, I.D., Hudson, M.D., 2013. Metal contamination in water, sediment and biota from a semi-enclosed coastal area. Environ. Monitor. Assess. 185, 3879–3895. http://dx.doi.org/10.1007/s10661-012-2837-0.

Anderson, M., Gorley, R.N., Clarke, R.K., 2008. Permanova+ for Primer: Guide to Software and Statistical Methods. Primer-E Limited.

Baird, A.H., Marshall, P.A., 2002. Mortality, growth and reproduction in scleractinian coral following bleaching on the great barrier reef. Mar. Ecol. Progr. Ser. 237, 133–141.

Barker, N.H.L., Roberts, C.M., 2004. Scuba diver behaviour and the management of diving impacts on coral reefs. Biol. Cons. 120, 481–489. http://dx.doi.org/10.1016/j.biocon.2004.03.021.

Batista, D., Muricy, G., Rocha, R.C., Miekeley, N.F., 2014. Marine sponges with contrasting life histories can be complementary biomonitors of heavy metal pollution in coastal ecosystems. Environ. Sci. Pollut. Res. 21, 5785–5794. http://dx.doi.org/10.1007/s11356-014-2530-7.

Bellwood, D.R., Hughes, T.P., Folke, C., Nyström, M., 2004. Confronting the coral reef crisis. Nature 429, 827–833. http://dx.doi.org/10.1038/nature02691.

Bosch, A., O'Neill, B., Sigge, G.O., Kerwath, S.E., Hoffman, L.C., 2015. Heavy metals in marine fish meat and consumer health: a review. J. Sci. Food Agric. 96, 32–48. http://dx.doi.org/10.1002/jsfa.7360.

Bri, M.J., Bustamante, P., Bonnet, X., Churlaud, C., Letourneur, Y., 2018. Tracking trace elements into complex coral reef trophic networks. Sci. Total Environ. 612, 1091–1104. http://dx.doi.org/10.1016/j.scitotenv.2017.08.257.

Burke, L., Reytar, K., Spalding, M.D., Perry, A., 2011. Reefs at risk: Revisited. World Resources Institue.

Cairns, J., van der Schalie, W.H., 1980. Biological monitoring part I-Early warning systems. Water Res. 14, 1179–1196. http://dx.doi.org/10.1016/0043-1354(80)90175-X.

Clarke, K.R., Warwick, R.M., 2001. Change in Marine Communities: An Approach to Statistical Analysis and Interpretation. PRIMER-E, Plymouth.

Cooper, T.F., Gilmour, J.P., Fabricius, K.E., 2009. Bioindicators of changes in water quality on coral reefs: Review and recommendations for monitoring programmes. Coral Reefs 28, 589–606. http://dx.doi.org/10.1007/s00338-009-0512-x.

Costanza, R., Arge, R., De, Groot.R., Farberk, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., Neill, R.V.O., Paruelo, J., Raskin, R.G., Suttonkk, P., van den, Belt M., 1997. The value of the world's ecosystem services and natural capital. Nature 387, 253–260. http://dx.doi.org/10.1038/387253a0.

De Wolf, H., Rashid, R., 2008. Heavy metal accumulation in littoraria scabra along polluted and pristine mangrove areas of tanzania. Environ. Pollut. 152, 636–643. http://dx.doi.org/10.1016/j.envpol.2007.06.064.

Dobaradaran, S., Soleimani, F., Nabipour, I., Saeedi, R., Mohammadi, M.J., 2018. Heavy metal levels of ballast waters in commercial ships entering Bushehr port along the Persian Gulf. Mar. Pollut. Bull. 126, 74–76. http://dx.doi.org/10.1016/j.marpolbul.2017.10.094.

Dunlap, M., Pawlik, J.R., 1996. Video-monitored predation by Caribbean reef fishes on an array of mangrove and reef sponges. Mar. Biol. 126, 117–123. http://dx.doi.org/10.1007/BF00571383.

Eakin, C.M., Sweatman, H.P.A., Brainard, R.E., 2019. The 2014–2017 global-scale coral bleaching event: insights and impacts. Coral Reefs 38, 539–545. http://dx.doi.org/10.1007/s00338-019-01844-2.

EC, 2011. (European Comission). Commission regulation (EC) No 420/2011 of 29 April 2011: amending regulation (EC) No 1881/2006 setting maximum levels for certain contaminants in foodstuffs. Official J. European Union, L 111, 3–6.

Elzhov, T.V., Mullen, K.M., Spiess, A., Bolker, B., 2010. R interface to the Levenberg–Marquardt nonlinear least-squares algorithm found in MINPACK. In: Plus Support for Bounds. pp. 1–2.

English, S.S., Wilkinson, C.C.R., Baker, V.V., 1997. Survey manual for tropical marine resources. Australian Institute of Marine Science.

Fabricius, K.E., 2005. Effects of terrestrial runoff on the ecology of corals and coral reefs: Review and synthesis. Mar. Pollut. Bull. 50, 125–146. http://dx.doi.org/10.1016/j.marpolbul.2004.11.028.

Folke, C., Kautsky, N., 1992. Aquaculture with its environment: Prospects for sustainability. Ocean Coast. Manag. 17, 5–24. http://dx.doi.org/10.1016/0964-5691(92)90059-T.

Gil, M.A., Renfro, B., Figueroa-Zavala, B., Penié, I., Dunton, K.H., 2015. Rapid tourism growth and declining coral reefs in Akumal, Mexico. Mar. Biol. 162, 2225–2233. http://dx.doi.org/10.1007/s00227-015-2748-z.

Guzmán, H.M., Jiménez, C.E., 1992. Contamination of coral reefs by heavy metals along the Caribbean coast of Central America (Costa Rica and Panama). Mar. Pollut. Bull. 24, 554–561. http://dx.doi.org/10.1016/0025-326X(92)90708-E.

Hall, C.M., 2001. Trends in ocean and coastal tourism: The end of the last frontier? Ocean Coast. Manag. 44, 601–618. http://dx.doi.org/10.1016/S0964-5691(01)00071-0.

Hardin, G., 1968. The tragedy of the commons. Science 162, 1243–1248. http://dx.doi.org/10.1126/science.162.3859.1243.

Harvey, J., 1977. Some aspects of the hydrography of the water off the coast of Tanzania: A contribution to CINCWIO. Univ. Sci. J. 3, 53–92.

Heikoop, J.M., Risk, M.J., Lazier, A.V., Edinger, E.N., Jompa, J., Limmon, G.V., Dunn, J.J., Browne, D.R., Schwarcz, H.P., 2000. Nitrogen-15 signals of anthropogenic nutrient loading in reef corals. Mar. Pollut. Bull. 40, 628–636. http://dx.doi.org/10.1016/S0025-326X(00)00006-0.

Herrán, N., Narayan, G.R., Reymond, C.E., Westphal, H., 2017. Calcium carbonate production, coral cover and diversity along a distance gradient from Stone Town: A case study from Zanzibar, Tanzania. Front. Mar. Sci. 4, 1–14. http://dx.doi.org/10.3389/fmars.2017.00412.

Hilderbrand, R.H., Watts, A.C., Randle, A.M., 2005. The myths of restoration ecology. Ecol. Soc. 10, 19.

Hill, J., Wilkinson, C., 2004. Methods for ecological monitoring of coral reefs. http://dx.doi.org/10.1017/CBO9781107415324.004.

Hodgson, G., 1999. A global assessment of human effects on coral reefs. Mar. Pollut. Bull. 38, 345–355. http://dx.doi.org/10.1016/S0025-326X(99)00002-8.

Hoegh-Guldberg, O., 1999. Climate change, coral bleaching and the future of the world's coral reefs. Mar. Freshwater Res. 50, 839–866. http://dx.doi.org/10.1071/MF99078.

Hönke, J., Cuesta-Fernandez, I., 2017. A topolographical approach to infrastructure: Political topography, topology and the port of dar es salaam. Environ. Plan. D: Soc. Space 35, 1076–1095. http://dx.doi.org/10.1177/0263775817707762.

Jennings, S., Kaiser, M.J., 1998. The Effects of Fishing on Marine Ecosystems. Elsevier Masson SAS, http://dx.doi.org/10.1016/S0065-2881(08)60212-6.

Jiddawi, N.S., Ohman, M.C., 2002. Marine fisheries in Tanzania. Ambio 31, 518–527. http://dx.doi.org/10.1579/0044-7447-31.7.518.

Johnstone, R.W., Muhando, C.A., Francis, J., 1998. The status of the coral reefs of Zanzibar: One example of a regional predicament. Ambio 27, 700–707.

Kassambara, A., 2020. ggpubr: 'ggplot2' Based Publication Ready Plots. R package version 0.4.0.

Kruitwagen, G., Pratap, H.B., Covaci, A., Wendelaar Bonga, S.E., 2008. Status of pollution in mangrove ecosystems along the coast of Tanzania. Mar. Pollut. Bull. 56, 1022–1031. http://dx.doi.org/10.1016/j.marpolbul.2008.02.018.

Lange, G.-M., Jiddawi, N., 2009. Economic value of marine ecosystem services in Zanzibar: Implications for marine conservation and sustainable development. Ocean Coast. Manage. 52, 521–532. http://dx.doi.org/10.1016/j.ocecoaman.2009.08.005.

Linton, D.M., Warner, G.F., 2003. Biological indicators in the caribbean coastal zone and their role in integrated coastal management. Ocean Coast. Manag. 46, 261–276. http://dx.doi.org/10.1016/S0964-5691(03)00007-3.

Lokrantz, J., Nyström, M., Albert, V.N., Folke, C., Cinner, J.E., 2010. Impacts of artisanal fishing on key functional groups and the potential vulnerability of coral reefs. Environ. Conserv. 36, 327–337. http://dx.doi.org/10.1017/S0376892910000147.

Loya, Y., 1978. Plotless and transect methods. In: Coral Reefs: Research Methods.

Mak, J., Moncur, J.E.T., 1995. Sustainable tourism development: Managing Hawaii's unique touristic resource – Hanauma bay. J. Travel Res. 33, 51–57. http://dx.doi.org/10.1177/004728759503300408.

Marten, G.G., 2001. Human Ecology: Basic Concepts for Sustainable Development. Earthscan Publications.

McClanahan, T.R., Ateweberhan, M., Graham, N.A.J., Wilson, S.K., Ruiz Sebastián, C., Guillaume, M.M.M., Bruggemann, J.H., 2007. Western Indian ocean coral communities: Bleaching responses and susceptibility to extinction. Mar. Ecol. Prog. Ser. 337, 1–13. http://dx.doi.org/10.3354/meps337001.

McClanahan, T.R., Muthiga, Na, Kamukuru, aT, Machano, H., Kiambo, R.W., 1999. The effects of marine parks and fishing on coral reefs of northern Tanzania. Biol. Cons. 89, 161–182. http://dx.doi.org/10.1016/S0006-3207(98)00123-2.

McClanahan, T.R., Sheppard, C.R.C., Obura, D.O., 2000. Coral Reefs of the Indian Ocean: Their Ecology and Conservation. Oxford University Press on Demand.

McCook, L.J., Jompa, J., Diaz-Pulido, G., 2001. Competition between corals and algae on coral reefs: A review of evidence and mechanisms. Coral Reefs 19, 400–417. http://dx.doi.org/10.1007/s003380000129.

McLean, B., Hikmany, A.-N., Mangora, M., Shalli, M., 2012. Legal and Institutional Framework for Effective Management of Marine Managed Areas in Tanzania Report on Zanzibar.

Melawaty, L., Noor, A., Harlim, T., Voogd, N. De, 2014. Essential metal Zn in sponge Callyspongia aerizusa from Spermonde Archipelago. Adv. Biol. Chem. 4, 86–90.

Mohammed, M.S., Muhando, C.A., Machano, H., 2000. Assessment of coral reef degradation in Tanzania: results of coral reef monitoring–1999. CORDIO.

Moynihan, M.A., Baker, D.M., Mmochi, A.J., 2012. Isotopic and microbial indicators of sewage pollution from Stone Town, Zanzibar, Tanzania. Mar. Pollut. Bull. http://dx.doi.org/10.1016/j.marpolbul.2012.05.001.

Muzuka, A.N.N., 2007. Distribution of heavy metals in the coastal marine surficial sediments in the msasani bay-dar es salaam harbour area. Western Indian Ocean J. Mar. Sci. 6, 73–83.

Muzuka, A.N.N., Dubi, A.M., Muhando, C.A., Shaghude, Y.W., 2010. Impact of hydrographic parameters and seasonal variation in sediment fluxes on coral status at Chumbe and Bawe reefs, Zanzibar, Tanzania. Estuar. Coast. Shelf Sci. 89, 137–144. http://dx.doi.org/10.1016/j.ecss.2010.05.007.

Negri, A., Burns, K., Boyle, S., Brinkman, D., Webster, N., 2006. Contamination in sediments, bivalves and sponges of McMurdo Sound, Antarctica. Environ. Pollut. 143, 456–467. http://dx.doi.org/10.1016/j.envpol.2005.12.005.

Neuwirth, E., 2014. RColorBrewer: ColorBrewer Palettes. R package version 1.1-2.

Nordlund, L.M., Kloiber, U., Carter, E., Riedmiller, S., 2013. Chumbe Island Coral Park-governance analysis. Mar. Policy 41, 110–117. http://dx.doi.org/10.1016/j.marpol.2012.12.018.

Norström, A.V., Nyström, M., Lokrantz, J., Folke, C., 2009. Alternative states on coral reefs: Beyond coral-macroalgal phase shifts. Mar. Ecol. Prog. Ser. 376, 293–306. http://dx.doi.org/10.3354/meps07815.

Nyanda, F., Mtei, R.P., Mohammed, S.M., Mmochi, A.J., 2016. Nutrient and bacteria concentrations in the coastal waters off Zanzibar town. WIO J. Mar. Sci. 15, 9–17. http://dx.doi.org/10.1038/278097a0.

Obura, D., Gudka, M., Rabi, F.A., Gian, S.B., Bijoux, J., Freed, S., Maharavo, J., Mwaura, J., Porter, S., Sola, E., Wickel, J., 2017. Coral reef status report for the Western Indian Ocean (2017). In: Nairobi Convention. Global Coral Reef Monitoring Network (GCRMN)/International Coral Reef Initiative (ICRI).

Oksanen, J., Blanchet, F.G., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., Minchin, P.R., O'Hara, R.B., Simpson, G.L., Solymos, P., Stevens, M.H.H., Szoecs, E., Wagner, H., 2020. Vegan: Community Ecology Package. R package version 2.5-7.F.

Pandolfi, J.M., Connolly, S.R., Marshall, D.J., Cohen, A.L., 2011. Projecting coral reef futures under global warming and ocean acidification. Science 333, 418–422. http://dx.doi.org/10.1126/science.1204794.

Pant, P., 2013. An Assessment of Heavy Metal Distribution in Mangrove Sediments Along the Coast of Zanzibar. VUB.

Paulay, G., 1997. Diversity and distribution of reef organisms. In: Life and Death of Coral Reefs. pp. 198–229.

PRC, 2012. (People's Republic of China). National food safety standard for maximum levels of contaminants in foods. National Standard of the People's Republic of China GB GB2762–2012, Beijing.

R Core Team, 2019. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria, URL https://www.R-project.org/.

Rainbow, P.S., Phillips, D.J.H., 1993. Cosmopolitan biomonitors of trace metals. Mar. Pollut. Bull. 26, 593–601. http://dx.doi.org/10.1016/0025-326X(93)90497-8.

Rao, J.V., Srikanth, K., Pallela, R., Rao, T.G., 2009. The use of marine sponge, Haliclona tenuiramosa as bioindicator to monitor heavy metal pollution in the coasts of Gulf of Mannar, India. Environ. Monit. Assess. 156, 451–459. http://dx.doi.org/10.1007/s10661-008-0497-x.

Rayment, G.E., Barry, G.A., 2000. Indicator tissues for heavy metal monitoring - Additional attributes. Mar. Pollut. Bull. 41, 353–358. http://dx.doi.org/10.1016/S0025-326X(00)00128-4.

Rogers, C.S., Miller, J., 2006. Permanent 'phase shifts' or reversible declines in coral cover? Lack of recovery of two coral reefs in St. John, US Virgin Islands. Mar. Ecol. Prog. Ser. 306, 103–114.

Ruitenbeek, J., Hewawasam, I., Ngoile, M., 2005. Blueprint 2050: Sustaining the Marine Environment in Mainland Tanzania and Zanzibar. The World Bank, Washington D.C.

Rumisha, C., Elskens, M., Leermakers, M., Kochzius, M., 2012. Trace metal pollution and its influence on the community structure of soft bottom molluscs in intertidal areas of the dar es salaam coast, Tanzania. Mar. Pollut. Bull. 64, 521–531. http://dx.doi.org/10.1016/j.marpolbul.2011.12.025.

Rumisha, C., Leermakers, M., Elskens, M., Mdegela, R.H., Gwakisa, P., Kochzius, M., 2017a. Genetic diversity of the giant tiger prawn Penaeus monodon in relation to trace metal pollution at the Tanzanian coast. Mar. Pollut. Bull. 114, 759–767.

Rumisha, C., Leermakers, M., Mdegela, R.H., Kochzius, M., Elskens, M., 2017b. Bioaccumulation and public health implications of trace metals in edible tissues of the crustaceans Scylla serrata and Penaeus monodon from the Tanzanian coast. Environ. Monit. Assess. 189, http://dx.doi.org/10.1007/s10661-017-6248-0.

Salm, R., Muhiga, N., Muhando, C.A., 1998. Status of coral reefs in the western Indian ocean and evolving coral reef programmes. In: Status of Coral Reefs of the World. 1998, pp. 53–63.

Sammarco, P.W., 1980. Diadema and its relationship to coral spat mortality: Grazing, competition, and biological disturbance. J. Exp. Mar. Biol. Ecol. 45, 245–272. http://dx.doi.org/10.1016/0022-0981(80)90061-1.

Sheikh, M.A., Noah, N.M., Tsuha, K., Oomori, T., 2007. Occurrence of tributyltin compounds and characteristics of heavy metals. Int. J. Environ. Sci. Technol. 4, 49–59.

Silva, P., 2006. Exploring the Linkages Between Poverty, Marine Protected Area Management, and the Use of Destructive Fishing Gear in Tanzania. World Bank Policy Research Working Paper 3831, pp. 1–43.

Staehr, P.A., Sheikh, M.A., Rashid, R., Kloiber, U., Dahl, K., Tairova, Z., Strand, J., Kuguru, B., Muhando, C., 2018. Managing human pressures to restore ecosystem health of zanzibar coastal waters. J. Aquac. Mar. Biol. 7 (2), 59–70. http://dx.doi.org/10.15406/jamb.2018.07.00185.

Storelli, M.M., Barone, G., Cuttone, G., Giungato, D., Garofalo, R., 2010. Occurrence of toxic metals (Hg, Cd and Pb) in fresh and canned tuna: public health implications. Food Chem. Toxicol. 48, 3167–3170.

Storlazzi, C.D., Field, M.E., Bothner, M.H., 2011. The use (and misuse) of sediment traps in coral reef environments: Theory, observations, and suggested protocols. Coral Reefs 30, 23–38. http://dx.doi.org/10.1007/s00338-010-0705-3.

Sutherland, R.A., 2000. Bed sediment-associated trace metals in an urban stream, Oahu, Hawaii. Environ. Geol. 39, 611–627. http://dx.doi.org/10.1007/s002540050473.

Thompson, R.C., Olsen, Y., Mitchell, R.P., Davis, A., Rowl, SJ, John, A.W.G., McGonigle, D., Russell, A.E., 2004. Lost at sea: where is all the plastic? Science 304 (838), http://dx.doi.org/10.1126/science.1094559.

Wedepohl, H.K., 1995. The composition of the continental crust. Geochim. Cosmochim. Acta 59, 1217–1232. http://dx.doi.org/10.1016/B978-0-08-095975-7.00301-6.

Wickham, H., 2016. Ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag, New York.

Wilson, S.P., Verlis, K.M., 2017. The ugly face of tourism: Marine debris pollution linked to visitation in the southern Great Barrier Reef, Australia. Mar. Pollut. Bull. 117, 239–246. http://dx.doi.org/10.1016/j.marpolbul.2017.01.036.

Wulff, J., 2017. Bottom-up and top-down controls on coral reef sponges: disentangling within-habitat and between-habitat processes. Ecology 98, 1130–1139. http://dx.doi.org/10.1002/ecy.1754.

Yongming, H., Peixuan, D., Junji, C., Posmentier, E.S., 2006. Multivariate analysis of heavy metal contamination in urban dusts of Xi'an, Central China. Sci. Total Environ. 355, 176–186. http://dx.doi.org/10.1016/j.scitotenv.2005.02.026.