Sources and spatial distribution of heavy metals in scleractinian coral tissues and sediments from the Bocas del Toro Archipelago, Panama

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Abstract Marine ecosystems worldwide are threatened by aquatic pollution; however, there is a paucity in data from the Caribbean region. As such, five heavy metals (arsenic, cadmium, copper, zinc, mercury) were measured in tissues of the scleractinian corals *Porites furcata* and *Agaricia tenuifolia* and in adjacent sediments in the Bocas del Toro Archipelago, Panama. Samples were collected from five reef sites along a gradient of distance from an international shipping port and were analysed using inductively coupled plasma optical emission spectrometry and atomic absorption spectrophotometry for mercury. Copper and zinc were the most abundant metals and ranged from 11 to 63 mg kg^{-1} and from 31 to 185 mg kg^{-1} in coral tissues, respectively. The highest concentration of each metal was measured in *P. furcata* tissues, with copper and mercury concentrations significantly higher in *P. furcata* than in *A. tenuifolia* at every site. These results suggest that *P. furcata* has a higher affinity for metal accumulation and storage than *A. tenuifolia*. With the exception of cadmium, metal concentrations in coral tissues were generally elevated at coral reefs in closer proximity to the port; however, this pattern was not observed in sediments. Hard coral cover was lowest at reefs in closest proximity to the port, suggesting that metal pollution from port-related activities is influencing hard coral abundance at nearby coral reefs.

Keywords Coral reef · Heavy metal · Sediments · Port · *Porites furcata* · *Agaricia tenuifolia*

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Introduction

Pollution poses a serious risk to the ecological balance of inshore coral reef systems and has been an important issue in the wider Caribbean region for the last

two decades (Fernandez et al. 2007; GESAMP 2001; United Nations Environment Program (UNEP) 1994). Heavy metals are major constituents of agro-chemicals, industrial pollutants commonly used in ports as well as domestic sewage (Guzmán and Jiménez 1992). They present a serious threat to the marine environment due to their potential toxic effects (Negri and Heyward 2001; Pastorok and Bilyard 1985), wide distribution and capacity for being transported to long distances via atmospheric and hydrological processes (Marx and McGowan 2010; Guzmán and Jiménez 1992).

Heavy metals can result in acute or chronic toxicity causing lethal effects or long-term impacts to key biological processes of corals such as respiration (Howard et al. 1986), fertilisation and metamorphosis (Reichelt-Brushett and Michalek-Wagner 2005; Reichelt-Brushett and Harrison 1999; Negri and Heyward 2001; Heyward 1988) and larvae settlement (Reichelt-Brushett and Harrison 2000; Goh 1991). For example, Heyward (1988) detected the complete inhibition of fertilisation in *Goniastrea aspera*, *Favites chinensis* and *Platygyra ryukyuensis* gametes when exposed to copper sulphate solutions greater than or equal to 0.5 mg L^{-1}. Heavy metals can also result in physiological stress (Howard and Brown 1984), loss of zooxanthellae (Esquivel 1986; Harland and Brown 1989), reduced growth (Howard and Brown 1987), enhanced mortality (Mitchelmore et al. 2007) and reduced biodiversity (Ramos et al. 2004).

Although heavy metals pose a variety of detrimental effects, studies examining heavy metal pollution in corals have received minimal attention worldwide, particularly in the wider Caribbean region. This is of concern since coastal regions of Central America are exposed to a large range of metal pollution from increased environmental contamination (Guzmán and Jiménez 1992). To the best of our knowledge, only three studies examining heavy metal contamination of corals from the wider Caribbean region have been published (Guzmán and García 2002; Guzmán and Jiménez 1992; Bastidas and García 1997). Two of these studies (Guzmán and García 2002; Guzmán and Jiménez 1992) analysed heavy metal concentrations in sediments and coral skeletons (*Siderastrea siderea*) along the eastern coast of Costa Rica and Panama and indicated intermediate to high levels of pollution (Guzmán and Jiménez 1992). The third study measured nine heavy metals in *Montastrea*

annularis tissues and skeletons (Bastidas and García 1997) and indicated no direct relationship between coral metal concentrations and sedimentation rates.

The objectives of the current study were to determine baseline concentrations and inter-species differences of heavy metals in the tissue of the region's two dominant shallow hard coral species: *Porites furcata* and *Agaricia tenuifolia*. Arsenic (As), cadmium (Cd), copper (Cu), zinc (Zn) and mercury (Hg) were analysed as these metals are considered to have the greatest toxic impact of all metals that enter the environment in elevated concentrations (Haynes and Johnson 2000). For this purpose, in situ coral and sediment collection was conducted from coral reef sites along a gradient of increased distance from the Port of Almirante. Results of this study provide further insight into some of the mechanisms influencing heavy metal accumulation in scleractinian corals and will also serve as baseline data for future comparisons of coral reef and sediment contamination by heavy metals within the Bocas del Toro Archipelago.

Materials and methods

Study area and sampling

Almirante Bay is a semi-enclosed lagoon system (Fig. 1) in the Bocas del Toro Archipelago, which is situated on the Caribbean Sea in Panama. The bay is influenced by ocean conditions via the Boca del Drago inlet situated in the north and experiences a small tidal range of 2–15 cm (Guzmán et al. 2005). A permanent gyre runs (in a counterclockwise direction) south along the coast of Costa Rica and Panama, suggesting long residence times of coastal waters (Guzmán and Jiménez 1992). The Changuinola River is the largest river in proximity to the bay, with the mouth situated approximately 11 km north-west of the Almirante Bay (Saric 2005). The Changuinola River runs adjacent to mainland banana plantations and discharges sediments into the ocean, which are then transported as a plume into the bay via the Boca del Drago inlet, exiting through the Bocas del Toro Channel and Crawl Cay Channel outlets (Saric 2005). Development is a national priority in the province of Bocas del Toro, and consequently, the marine environment within the bay is severely impacted by sewage discharge, overfishing,

dredging and a commercial shipping port that is situated close to the mainland and the town of Almirante (Burke et al. 2004; Guzmán and Jiménez 1992). The Port of Almirante exports bananas and is the only industrial source of heavy metals within Almirante Bay.

Coral reef survey sites were chosen based on their proximity to the port: Almirante "AL"=~1.5 km, Pastores "PA"=~8 km, Juan Point "JP"=~10 km, Casa Blanca "CB"=~18 km and Salt Creek "SC"=~35 km away (Fig. 1). Sampling was conducted three times from November 2010 to January 2011. Due to the lack of background contamination data from this area, coral reef monitoring was conducted throughout the bay using international Reef Check guidelines (Hodgson 2000) to assess the suitability of reefs to be used as experimental sites. Transect monitoring was conducted in replicates of three per reef, at depths of 1–5 and 6–10 m. Substrate composition, coral diversity and abundance were recorded. Monitoring also provided information on eutrophication based on the presence of high-nutrient indicator species. Water samples (three replicates/sampling) were taken from a 3-m depth using a 2-L Niskin bottle and were immediately analysed for temperature and salinity using a probe (WTW Multiline P4). Sediment samples were taken in cores from the top 10 cm (n=3/sampling period) of substrate surrounding reef sites and oven-dried at 40 °C for 1 week. Dry sediments were sieved into the size fractions of <125 μm.

P. furcata was cut using pliers, while *A. tenuifolia* was taken using hammer and chisel. Baseline survey fragments were collected (n=15/species) from random colonies between 1- and 6-m depth at all five sites. Due to insufficient tissue mass for analysis, only 11–14 fragments could be analysed per site. Sampled fragments were placed in plastic bags and transported on ice to the Smithsonian Tropical Research Institute where they were frozen (−20 °C) until processing. The tissue component of the coral was chosen for heavy metal analyses since metals such as Zn are important for biological functions and accumulate in greater concentrations in coral tissue relative to skeleton (Anu et al. 2007). In studies comparing both tissue and skeleton components, concentrations of metals in skeletons were typically lower than those recorded in tissues (Howard and Brown 1987; McChonchie and Harriott 1992; Bastidas and García 1997; Reichelt-Brushett and McOrist 2003).

Thawed fragments were rinsed thoroughly with filtered seawater to remove sediments and organic debris. Coral tissues were removed from the skeleton with an air gun and a constant volume of filtered seawater. Floating tissues from individual fragments were collected with a sterile dropper and placed into a single, pre-weighed 15-mL centrifuge tube. Remaining tissue slurry was centrifuged at 4,000 rpm (Eppendorf 5810 R) for 10 min. After centrifugation, the concentrates (tissues and zooxanthellae) were added to the pre-weighed centrifuge tube using a sterile dropper, which was then centrifuged for an additional 5 min in order to concentrate the remaining suspended tissue components. The supernatant was discarded, and the pre-weighed tube was then oven-dried (60 °C for approximately 72 h) until a constant weight was maintained.

Digestion procedures

Dry tissue and sediment samples were milled using an agate pestle and mortar that was cleaned with 70 % ethanol between each sample. Depending on the sample amount, 50–100 mg of ground tissue and approximately 100 mg of the ground sediments were weighed into Teflon PDS-6 vessels (Heinrichs et al. 1986). Tissues were treated for 1 h with 1 mL of 65 % nitric acid (HNO_3) to oxidise organic matter. Afterwards, 2 mL of 60 % perchloric acid ($HClO_4$) was added and the material was digested in closed vessels for 6 h at 180 °C. Acids were then evaporated on a heated metal block (180 °C), redissolved and fumed off three times with 2 mL of diluted hydrochloric acid (HCl, 1 part HCl to 1 part deionised water). Finally, the samples were diluted to a volume of 2 mL with 2 % HNO_3. Acid digestions of sediments were similar to the methods described for tissues, substituting 3 mL of 40 % hydrofluoric acid and 1 mL of 60 % $HClO_4$ instead of 2 mL of 60 % $HClO_4$ before heating the vessels for 6 h at 180 °C.

Instrumental analyses

The heavy metals As, Cd, Cu and Zn were analysed by inductively coupled plasma optical emission spectrometry (iCAP 6300 Duo, Thermo Fisher Scientific) with detection limits of 1.4, 0.04, 0.24 and 1.2 μg L^{-1}, respectively. The interference of Fe on the Cd wavelength 214.4 nm was corrected by measuring the apparent Cd concentration produced by a pure Fe solution. Precision and accuracy were checked every 12th sample by analysing the certified reference
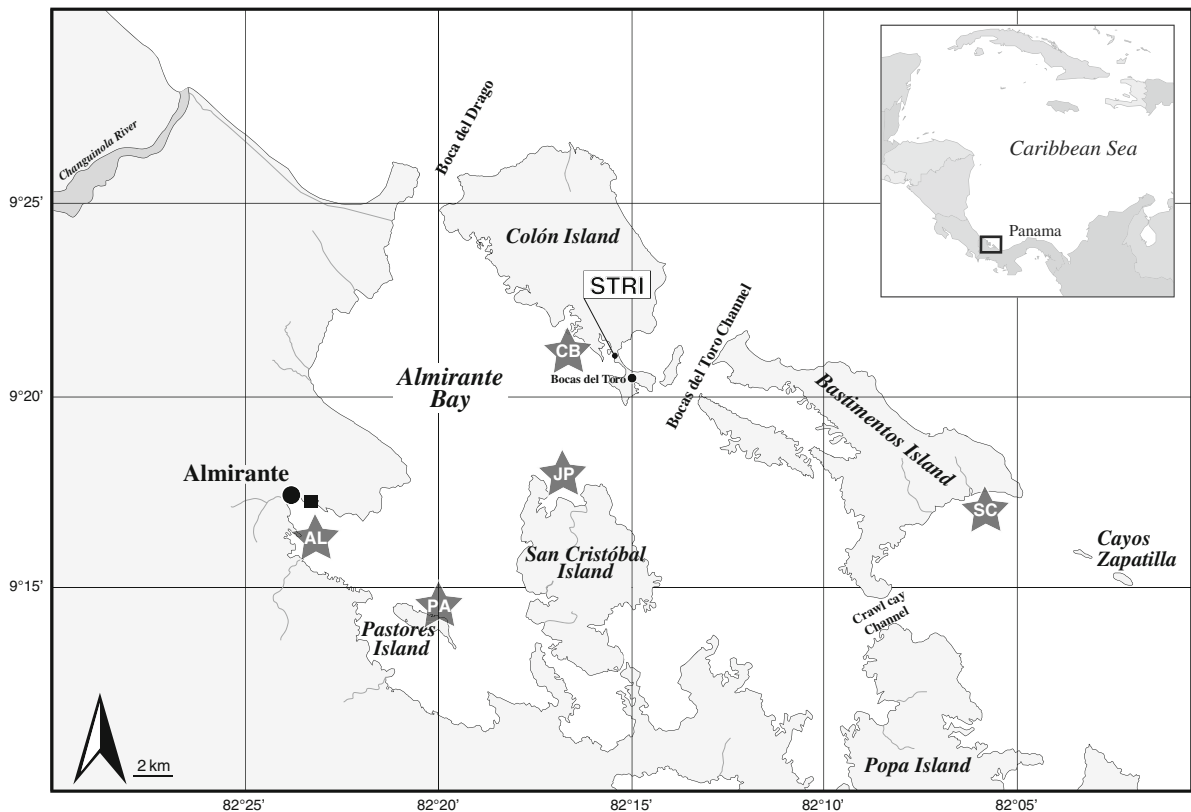
Fig. 1 Survey sites within the Bocas del Toro Archipelago are depicted by *grey stars*. *AL*=Almirante, *PA*=Pastores, *JP*=Juan Point, *CB*=Casa Blanca, *SC*=Salt Creek, *STRI*=Smithsonian Tropical Research Institute. Commercial shipping vessels enter the bay through the Boca del Drago inlet in the north and proceed to the Port of Almirante (*black square*). The town of Almirante is represented by the *black circle*

material TH-2 (Environment Canada, National Water Research Institute, Burlington, Canada) and were <5.0 and <6.4 %, respectively. The concentration of Hg in homogenised dry coral tissues and sediments was analysed using atomic absorption spectrophotometry (Direct Mercury Analyzer 80, Milestone), with an absolute detection limit of 0.0015 ng Hg. Approximately 100 mg of the ground material was pre-weighed in an aluminium boat and transferred to the auto-sampler of the analytical instrument. A standard and blank were analysed after every 10 samples. The calculated precision and accuracy were 4.0 and 3.4 %, respectively.

Data analyses

All analyses were conducted using SigmaStat 11.0 (SYSTAT Software Inc.), with the exception of cluster, for which SPSS version 20 for Windows (Chicago, IL) was used. Normality of data was tested using a Shapiro–Wilk test. Differences in heavy metal concentrations among sites and between species were evaluated using a Kruskal–Wallis one-way ANOVA based on ranks and Dunn's method for post hoc tests. To analyse associations between metal abundance and survey sites, a hierarchical cluster analysis was run for sediments and each species individually. Spearman's rank order correlation was used to determine associations between metal concentrations in corals and distance from the port. All statistical values are presented as means±standard error.

Results and discussion

Environmental parameters

No significant differences were found in temperature (mean=26.8±0.6 °C) or salinity (mean=31.8± 0.2 g kg^{-1}) between sampling sites. The mean percent

of live hard coral cover recorded at the survey sites generally increased with distance from the port (AL, 21.4±5 %; PA, 22.5±6 %; JP, 32.6±5 %; CB, 25.3± 8 %; SC, 45.9±2 %). Hard coral cover at SC was significantly higher than at PA ($p=0.035$) and AL ($p=0.033$). Both *P. furcata* and *A. tenuifolia* were found in the shallow reef areas at all survey sites with the exception of AL, at which hard coral cover was dominated by *P. furcata* (>90 %) and no *A. tenuifolia* (0 %) was observed at this reef.

Heavy metals in sediments

Figure 2 illustrates the mean concentrations of As, Cd, Cu, Zn and Hg in reef sediments. The ranking order of heavy metals in sediments was Zn>Cu>As>Cd>Hg. Cluster analysis separated sites into three main clusters based on heavy metal concentrations in sediments (Fig. 3a). Metal concentrations at PA, JP and CB were strongly associated to each other, followed by AL. Metal concentrations at SC were weakly associated with the other sites; however, no significant differences were found between sites for any metal. AL contained the highest concentration of Hg (22.9± 8 $\mu g\ kg^{-1}$) in sediments, while SC contained the highest concentrations of Cu (78.6±31 $mg\ kg^{-1}$) and Zn (79.9±34 $mg\ kg^{-1}$). The concentration of As and Cd in sediments was very low in comparison to the other metals. The higher concentrations of Cu and Zn found at SC (the most offshore site) demonstrate the persistence and long-distance transportation of aquatic pollution from input sources to more remote areas of the marine environment. Other than the Port of Almirante, the only other industrial source of metal pollution in the Bocas del Toro Archipelago is an oil refinery located approximately 40 km south-west of SC in the Chiriquí Lagoon. With the exception of Cu, all metals measured in sediments were below contamination levels stated by the US Environmental Protection Agency (Long et al. 1995). Sites AL, PA, JP and SC exceeded the "effects range low" (ERL) guideline value of Cu (>34 $mg\ kg^{-1}$). The ERL is not a threshold limit, but rather the upper range of Cu concentrations where effects to biota are rarely observed (Long and Morgan 1990). Thus, Cu adsorbed to sediments within the Almirante Bay could be negatively impacting biota; however, the sediments are considered within natural environmental background levels for As, Cd, Zn and Hg.

Studies conducted by Guzmán and Jiménez (1992) and Guzmán and García (2002) measured Cu, Zn, Cd and Hg concentrations in sediments from sites in proximity to CB, JP and SC. In comparison to their results, the present study found a lower abundance of Cd and Hg and higher abundance of Cu and Zn in sediments at all sites. Variations found between these studies could be due to changes in levels of pollution discharge over time, availability of metals for adsorption as well as variations in the sampling season.

Comparison of heavy metals in coral tissues

Mean metal concentrations in coral tissues and significant ($p<0.05$) inter-site differences between species (ANOVA) are also provided in Fig. 2. The ranking order of heavy metals in coral tissue was Zn>Cu>As>Cd> Hg, and the highest concentrations of all metals analysed were in *P. furcata* tissues.

Metals are incorporated into corals via three main transport routes: solubilised forms, particulate forms and from food sources through bioaccumulation (Howard and Brown 1984). Although metals in solution are often in biologically available forms, metals in particulate and food phases are considered more important sources to marine organisms because they comprise higher heavy metal concentrations (Bryan 1980). The higher metal loads in *P. furcata* tissues could be related to differences in feeding mechanisms between the two species. *P. furcata* is more efficient at capturing zooplankton than *A. tenuifolia* (Lewis and Price 1975), which is more reliant on autotrophy for attaining its energy requirements (Seemann et al. 2012). Although the expansion of mucus nets from *A. tenuifolia* results in the ingestion of large amounts of fine particulate matter (Lewis and Price 1975), which is likely a significant source of heavy metals to this species, zooplankton accumulates metals such as Cd, Cu and Zn that biomagnify in the food web (Pempkowiak et al. 2005).

In comparison with other studies examining heavy metals in coral tissues sampled from reefs situated near marinas, harbours and ports (Table 1), concentrations of Cd, Cu and Zn in the present study were higher than those detected at Heron Island and Wistari Reef in Australia (McChonchie and Harriott 1992). The highest Cu concentration measured in their study (15 $mg\ kg^{-1}$ in *Goniastrea favulus* tissues) was similar to the less contaminated Cu sites in the Bocas del Toro Archipelago. The mean concentration of Zn

Fig. 2 Mean metal concentrations measured in *P. furcata*, *A. tenuifolia* and sediments at each experimental site in the Bocas del Toro Archipelago. *AL*=Almirante, *PA*=Pastores, *JP*=Juan Point, *CB*=Casa Blanca, *SC*=Salt Creek. *=$p<0.05$, intra-site significant differences in tissue metal concentrations between coral species
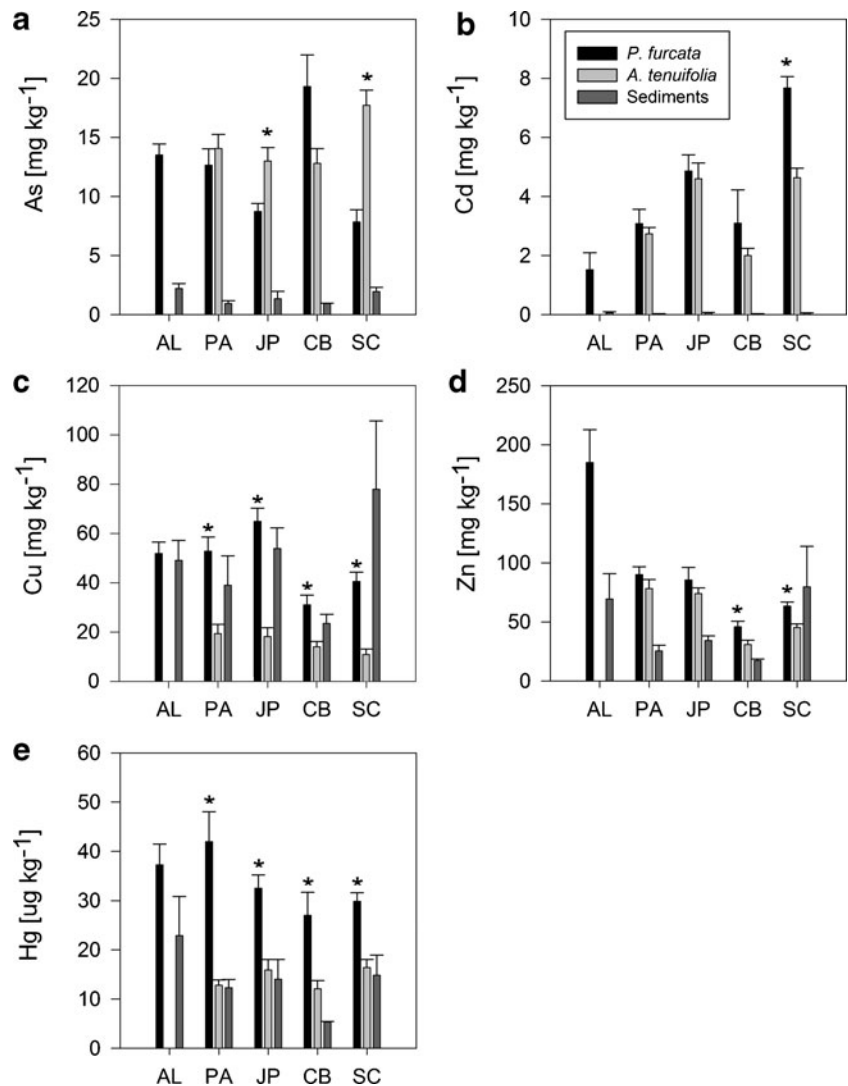
in *Pocillopora damicornis* (80 mg kg^{-1}) at Heron Island marina was approximately 105 mg kg^{-1} lower than the highest tissue concentration found in the present study. Similar to our results, the mean Zn concentration detected in coral tissues from the Heron Island marina was higher (up to five times) than those collected outside the marina area (Wistari Reef). Cu concentrations were also higher in the tissues of *G. favulus* and *Porites* spp. at the marina reef. Compared with our results, Esslemont (2000) detected a similar range of Cd concentrations at two coral reefs in proximity to the Port of Townsville, Australia, while Cu was generally higher in the present study (Table 1). Tissues of *Goniastrea aspera* sampled from close proximity to the Port of Townsville were substantially higher in Zn (mean = 900 mg kg^{-1}) than coral tissues

measured in the present study. However, Zn in *P. damicornis* and *Acropora formosa* tissues sampled from Nelly Bay Harbour (15 km offshore from the port) were only slightly higher than the Zn concentrations detected in *P. furcata* from AL. Variations in metal concentrations between these studies are related to differences in the types of metal source, the amount of pollution being released into the environment, the proximity of the respective coral reefs to the pollution source and species-specific affinities for metal uptake and storage. For example, the Port of Townsville is the principal port in North Queensland and serves a large area that includes the mining community at Mount Isa and the Greenvale nickel refinery (Queensland Government 2013). The main imports include refined fuel products, nickel ore, etc., while exports include
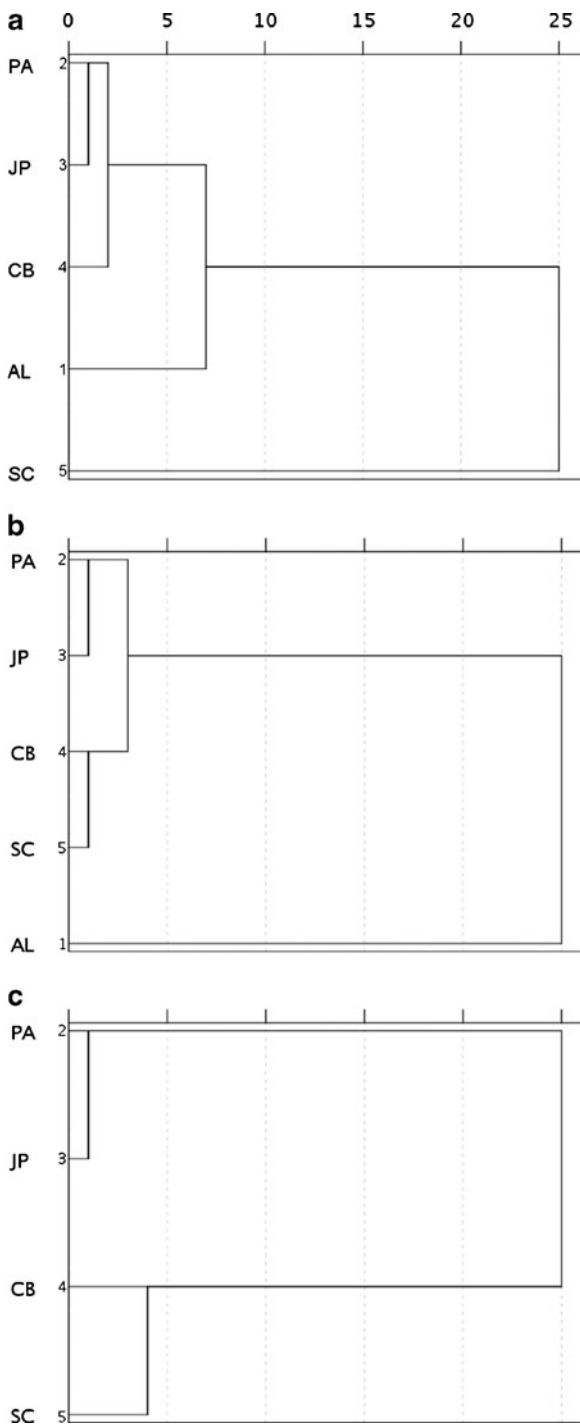
Fig. 3 Cluster analysis dendogram using average linkage between groups (x-axis) to illustrate associations between surveyed coral reef sites (y-axis) based on heavy metal concentrations measured in sediments (**a**), *P. furcata* (**b**) and *A. tenuifolia* (**c**) tissues. Site AL is omitted in **c** since *A. tenuifolia* did not naturally inhabit this site. AL=Almirante, PA=Pastores, JP=Juan Point, CB=Casa Blanca, SC=Salt Creek. *Numbers 1–5* represent the distance gradient of sites from the Port of Almirante, with *1* being the closest and *5* the farthest

antifoulants are the principal sources of metal pollution from the Port of Almirante.

Sources and distribution of heavy metals in coral tissues

Species-specific differences in tissue metal concentrations between sites are summarised in Table 2. A significant negative correlation was found for As, Hg, Cu and Zn concentrations with distance from the port in *P. furcata* and Cu and Zn in *A. tenuifolia* (Table 3). A significant positive correlation was found for Cd concentrations in both species. Heavy metal concentrations in coral tissues were separated into three clusters for *P. furcata* (Fig. 3b) and two clusters for *A. tenuifolia* (Fig. 3c). For both species, the first cluster revealed a strong association in metal concentrations between nearshore coral reef sites, situated in closer proximity to the port and town (PA and JP). The second cluster revealed a strong association of metal concentrations between corals at the more offshore reef sites (CB and SC). For *P. furcata*, site AL was weakly associated with the other four sites. This distinction between reefs is likely a result of differences in metal source and the hydrodynamics of the bay.

There are numerous sources of heavy metal pollution throughout Almirante Bay. Point sources include the Port of Almirante, while non-point sources include domestic sewage, agricultural activities and unpredictable sources such as oil waste by tankers (Guzmán and Jiménez 1992). Influence of wind, tides and surf are noticeably reduced inside this semi-lagoon system (Guzmán et al. 2005); thus, the distribution of metal pollution throughout the bay is likely facilitated by the resuspension of dredged sediments, water flow created by the inlet and outlets, discharge from rivers within the bay and the sediment plume originating from the Changuinola River that enters the bay via the Boca del Drago inlet.

The port and town of Almirante, as well as mainland river discharge, are the main pollution sources to nearshore coral reefs in Almirante Bay. AL showed the

copper and zinc concentrates, refined lead, copper, zinc and nickel (Queensland Government 2013). Thus, metal pollution in the environment surrounding this port can be attributed to many metal-related industries, whereas only port-related activities and

Table 1 Mean heavy metal concentrations in coral tissues from previous marina/harbour/port studies

Species	Analysis	Heavy metal concentration [mg kg^{-1}]			
		As & Hg	Cd	Cu	Zn
G. aspera[a]	Dry wgt.	–	2	37	900
P. damicornis[a]	Dry wgt.	–	6	13	209
A. formosa[a]	Dry wgt.	–	4	12	236
A. aspera[b]	Wet wgt.	–	2	5	71
A. valida[b]	Wet wgt.	–	2	3	35
P. damicornis[b]	Wet wgt.	–	2	4	80
G. favulus[b]	Wet wgt.	–	2	15	60
Porites spp.[b]	Wet wgt.	–	2	5	52

En dashes indicate that the metal was not analysed

[a] Source: Esslemont (2000). Comparisons were made using the values from Esslemont's heavy metal extraction procedure A. Values were converted from nM g^{-1} to mg kg^{-1}

[b] Source: McChonchie and Harriott (1992)

weakest association between all survey sites due to the high Zn concentrations in *P. furcata* tissues, which were significantly higher (185 ± 27 mg kg^{-1}) than the concentrations detected at CB (46 ± 5 mg kg^{-1}) and SC (63 ± 4 mg kg^{-1}, Table 2) and double the second highest mean concentration that was detected at PA (90 ± 7 mg kg^{-1}, Fig. 2). In general, mean Zn concentrations were significantly higher at near-shore reef sites compared to the more offshore reef sites for both species (see Table 2), with concentrations at PA and JP approximately double the mean concentrations at CB. Mean Cu concentrations were also higher at JP, PA and AL compared to CB and SC (Fig. 2); however, there were fewer significant

differences between sites (Table 2). Cu and Zn are the main components in organotin-free antifouling products used to eliminate the settlement of algae and marine invertebrates on ships and are commonly found in high levels around ports and harbours (Negri and Heyward 2001; Turner 2010). These metals are leached uncontrollably into the aquatic environment and antifoulant paint can contaminate sediments, harming many non-target marine invertebrates such as corals (Negri and Heyward 2001; Negri et al. 2002; Smith et al. 2003). Metals are also released into the marine environment at ports as a result of oil spills during terminal transfers and fuel discharge (Guzmán and Jiménez 1992).

Table 2 Significant differences found in *P. furcata* and (*A. tenuifolia*) tissues for each metal between sampling sites

Metal	Sites	Almirante	Pastores	Juan Point	Casa Blanca	Salt Creek
As	Juan Point	*	*	*	$p<0.05$	*
	Salt Creek	$p<0.05$	*	*	$p<0.05$	*
Cd	Almirante	*	*	$p<0.05$	*	$p<0.05$
	Pastores	*	*	($p<0.05$)	*	$p<0.05$ ($p<0.05$)
	Casa Blanca	*	*	($p<0.05$)	*	$p<0.05$ ($p<0.05$)
Cu	Casa Blanca	*	*	$p<0.05$	*	*
	Salt Creek	*	($p<0.05$)	*	*	*
Zn	Casa Blanca	$p<0.05$	$p<0.05$ ($p<0.05$)	($p<0.05$)	*	*
	Salt Creek	$p<0.05$	($p<0.05$)	($p<0.05$)	*	*

Corals sampled from sites listed on the top row are significantly higher than those from sites listed in the column and should be read accordingly. Sites and metals that showed no significant differences were omitted

*$p>0.05$ (not significantly different)

Inhibition of fertilisation and metamorphosis was observed in *Acropora millepora* after exposure to antifoulants and Cu (Negri and Heyward 2001). Cu concentrations of 42 and 81 μg L^{-1} significantly reduced the settlement success of *Acropora tenuis* larvae after 48 h of exposure (Reichelt-Brushett and Harrison 2000). Zn is important for coral photosynthesis and calcification; however, it can be toxic at high concentrations (Ferrier-Pagès et al. 2005). Heyward (1988) found that Zn sulphate concentrations of 1,000 μg L^{-1} reduced fertilisation rates of *P. ryukyuensis* and *F. chinensis* gametes. Direct comparisons cannot be made to these studies since the concentration of heavy metals in seawater was not analysed in the present study. However, the elevated Cu and Zn concentrations detected in sediments and coral tissue suggest that these metals could be the contributing factors to the reduced hard coral cover and diversity recorded at reefs in proximity to the port.

Although a significant negative correlation was found for Hg concentrations in *P. furcata* tissues with distance from the port, no clear pattern of distribution was found for Hg in *A. tenuifolia* (Table 3). Hg is not an essential element for biological functions, and any accumulation of Hg is considered as contamination and potentially hazardous (National Research Council 2000). A potential issue of concern is that Hg is known to biomagnify through trophic levels (United States Environmental Protection Agency 1997) and corallivorous fish from Almirante Bay, such as parrotfish, are being consumed by humans (personal observation).

Concentrations of Cd in coral tissue showed a significant positive correlation with distance from the port (Table 3). Low Cd content within corals located near ports and harbours has also been observed in other studies (McChonchie and Harriott 1992; Esslemont 2000) and was attributed to differences in water circulation and current distribution (McChonchie and Harriott 1992), as well as tissue regulation through assimilation of Cd into coral skeletons (Esslemont

2000). Heavy metals interact and compete for chemically similar ions when in solution (Ray 1986). The addition of Zn to seawater with Cd resulted in decreased Cd levels in the bivalves *Mytilus edulis* and *Mulinia lateralis* (Jackim et al. 1977). Thus, higher Zn levels in the port vicinity could account for the lower Cd concentrations measured in coral tissue.

The more offshore sites (CB and SC) generally contained lower concentrations of Cu and Zn, but higher concentrations of As (CB and SC) and Cd (SC). Potential sources of Cd and As to these reefs are sewage discharge from the highly developed and touristic Colón Island and biocides and fertilisers from river run-off entering the Boca del Drago inlet via the sediment plume. Metals are adsorbed to sediment particles, which play a significant role in their transport from pollution sources (Förstner and Salomons 1980). The higher metal concentrations found at SC compared to CB demonstrate that even remote coral reefs are influenced by metal pollution due to long-distance transport and persistence of metals in the marine environment. It is possible that SC is also being influenced by the oil refinery located to its south in the Chiriquí Lagoon. Due to the locality of these sites relative to the inlet (CB) and the open ocean (SC), higher water flow rates would result in a lower retention time of pollutants at CB and SC compared to the other sites and supports our finding of lower tissue concentrations of most metals detected at these sites (Fig. 2).

Conclusions

All of the surveyed coral reef sites within Almirante Bay and the surrounding archipelago are being influenced by heavy metal pollution; however, the near-shore coral reefs are at a greater risk from Cu, Zn and Hg pollution than the more offshore coral reefs. Cu and Zn are the most abundant metals in Almirante Bay, and antifoulants and port-related

Table 3 Correlation coefficients between mean tissue heavy metal concentrations and increasing distance from the Port of Almirante

Species	Correlation coeff.	Number	As	Cd	Cu	Zn	Hg
P. furcata	*r*	57	−0.34	+0.68	−0.27	−0.66	−0.29
	p value		$p=0.01$	$p<0.001$	$p=0.04$	$p<0.001$	$p=0.04$
A. tenuifolia	*r*	38	+0.30	+0.49	−0.49	−0.65	+0.22
	p value		$p=0.068$	$p=0.003$	$p=0.002$	$p<0.001$	$p=0.224$

activities are largely influencing Cu and Zn pollution to nearby coral reefs. These metals have increased in reef sediments over the last two decades, and currently, four out of the five survey sites exceed the ERL guideline value of Cu in sediments, meaning that the health of biota inhabiting these reefs could be at risk. The lower hard coral abundance and diversity at coral reefs in closer proximity to the port shows that these reefs are suffering from degraded environmental conditions and that management of these important ecosystems is required.

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