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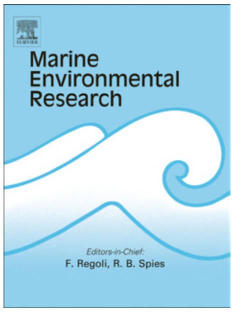
Accepted Manuscript



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PII: S0141-1136(10)00194-7
DOI: 10.1016/j.marenvres.2010.12.006
Reference: MERE 3494

To appear in: *Marine Environmental Research*

Received Date: 10 December 2009
Revised Date: 16 December 2010
Accepted Date: 18 December 2010

Please cite this article as: Hédouin, L., Metian, M., Gates, R.D. Ecotoxicological approach for assessing the contamination of a Hawaiian coral reef ecosystem (Honolua Bay, Maui) by metals and a metalloid, Marine Environmental Research (2010), doi: 10.1016/j.marenvres.2010.12.006

Ecotoxicological approach for assessing the contamination of a Hawaiian coral reef ecosystem (Honolua Bay, Maui) by metals and a metalloid

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Abstract

The goal of this study was to assess the contamination of Honolua Bay using an ecotoxicological approach. First, the concentrations of 9 contaminants (metals and metalloid) were assessed in sediments and tropical marine organisms (alga *Halimeda kanaloana*, goatfish *Parupeneus multifasciatus* and urchin *Tripneustes gratilla*) sampled from Honolua and surrounding Bays. Then, the ecological parameters characterizing coral health (e.g. coral cover) were evaluated in Honolua Bay in the context of these contaminants. High concentrations of Co, Cr, Mn, Ni, and V in sediments from Honolua and Honokohau Bay were measured, but these concentrations were not mirrored in the organisms examined, except for Mn, suggesting that the metals are generally bound in chemically inert forms in these sediments. Moreover, few anthropogenic activities impact these bays and so the elevated Co, Cr, Mn, Ni and V concentrations in sediments appear to stem from their high natural background in Honolua and Honokohau watersheds. An analysis of the relationship between the ecological parameters and metal concentrations in Honolua Bay revealed a significant correlation between coral cover and Co, Cr, Mn, Ni, V, Zn concentrations in sediments, with coral cover decreasing with increasing metal concentration. Collectively, however, the data suggest that a complex mixture of land-based stressors (e.g. sediment, metals, nutrients) affect the coral health in Honolua Bay, rather than metal stress alone.

Keywords: Hawaii, Ecology, Metals, Coral Reefs, Urchin, Algae

1. INTRODUCTION

Coral reefs are one of the most diverse and biologically complex marine ecosystems on earth. However there is now deep concern whether coral reefs will survive shifts in the marine environment associated with global changes and local stresses (e.g. Hoegh-Guldberg et al. 2007, Wilkinson 1999). Bryant et al (1998) report that 58 percent of the world's reefs are at risk from human activities, and that coastal development poses one of the most serious among these threats. Indeed, the expansion of human populations in coastal areas and the accompanying urbanization and agricultural activities, have increased the discharge of industrial wastes and untreated sewages onto the adjacent coral reefs. Such local activities have resulted in high metal concentrations in seawater, sediments, corals and tissues of other reef organisms sampled from a number of tropical ecosystems (e.g. Brown and Holley 1982, Hanna and Muir 1990). The adverse effects of metal contaminants on coral reefs have led to reduced growth and reproduction, coral death and loss of biodiversity (e.g. Negri et al. 2002, Richmond 1993). Metals have also been recognized as an environmental trigger that can induce bleaching of corals (e.g. David 2003, Scott and Davies 1997). As such, metal contamination in urban aquatic ecosystems is a major concern. In the Hawaiian Islands, a combination of basaltic rocks and large human populations with high traffic densities have led to elevated concentrations of copper, chromium, lead and zinc in streambed sediments (Andrews and Sutherland 2004, McMurtry et al. 1995), which in some cases, exceed the aquatic-life guidelines (De Carlo et al. 2005). While metal concentrations in streambed sediments from the Hawaiian Islands are relatively well known, with the exception of two studies, one in Kane‘ohe Bay (Hunter et al. 1995) and one in French Frigate Shoals in the North Western Hawaiian Islands (Miao et al. 2001), concentrations in sediments and biota from coastal reef areas are not well characterized. To address this knowledge gap, the Coral Reef Land Based Pollution Local Action Strategy (CRLBP-LAS) identified three watersheds in the main Hawaiian Islands as focal areas for studies to better understand the threats that land-based contaminants pose to the near shore coral reef ecosystems. Within this framework, an assessment of metal and metalloid concentrations in three reef sites revealed very high concentrations of Co, Cr, Ni and Mn in sediments from Honolua Bay, Maui (<464 µg Ni g^{-1} dwt) as compared to the Southern fringing reef of Moloka‘i and Kane‘ohe Bay, Oahu (<27 µg Ni g^{-1} dwt; Hédouin et al. 2009). Ni concentrations in Honolua Bay were 9 times higher than the Effective Range-Median for Sediment Quality Criteria (Long et al. 1995, NOAA 1999), which is in the range observed in reef areas impacted by Ni mining activities such as in New Caledonia (e.g. 797 to 900 g Ni g^{-1} dwt, Hédouin et al. 2008a), and definitely high enough to elicit adverse biological effects.

The difference between contamination and pollution is sometimes misunderstood and thus the terms are often misused. All pollutants are contaminants, but not all contaminants are pollutants (Chapman 2007, Warnau 1996). Elements or compounds are considered as contaminants when they are in concentrations over natural background whereas contaminants are considered as pollutants when they have an anthropogenic origin and negatively influence the environment, organisms, human health or human activities (GESAMP 1984). Metals and metalloid are naturally present in earth (Salomons and Forstner 1984), so their presence in sediments and biota is not always indicative of pollution. For this reason, we use the term contamination and contaminant to refer to the metals and metalloid in this paper.

The aims of the present study were to: 1) evaluate whether contaminant concentrations measured in Honolua Bay are unique to this bay by providing a comprehensive baseline of Arsenic (As), cobalt (Co), chromium (Cr), copper (Cu), manganese (Mn), nickel (Ni), lead (Pb), vanadium (V) and zinc (Zn) in reef sediments from Honolua Bay and adjacent bays in the West Maui region; 2) assess the bioavailability of metals and metalloid to the reef biota (the alga *Halimeda kanaloana*, the goatfish *Parupeneus multifasciatus* and the urchin *Tripneustes gratilla*); and 3) explore the relationship between coral ecology and the gradient of metal and metalloid contamination in Honolua Bay.

2. Materials and Methods

2.1. Description of Honolua Bay, West Maui, Hawai‘i

Honolua Bay has been a Marine Life Conservation District since 1978 and is divided into 3 broad regions (Fig. 1), that include (1) a fringing reef that extends into the bay and borders the north and south shorelines with a coral cover averaging 10.3 % on the north side and 23.3 % on the south side (CRAMP 2004), (2) a deeper sandy bottom area localized between the reefs, and (3) an inner bay composed of silt, sand, boulder bottom with corals present but reefs absent. This last area is the closest to the Honolua Stream and reflects this proximity by in its higher turbidity, lower salinity and higher dissolved nutrients (e.g. NO_3^-) (Marine Research Consultants Inc 2007). Honolua Stream is an interrupted perennial stream with an average stream flow of 19 million liters d^{-1} in the upper elevations. A detailed description of coastal circulation and sediment dynamics of the study area has been conducted by the United States Geological Survey (USGS) (e.g. Storlazzi and Jaffe 2003, Storlazzi et al. 2004, Storlazzi and Presto 2005).

2.2. Sample collection for metal and metalloid analyses

Four stations were selected in Honolua Bay for this study, two in the inner bay (Honolua1 = Hon1, Honolua3 = Hon3) and two on the reef bed offshore (Honolua2 = Hon2, Honolua4 = Hon4; Fig. 1). To better understand the degree of contamination in West Maui relative to Honolua Bay, other sampling sites were selected North of Honolua Bay (Honokohau Bay and

Lipoa Point) and South of Honolua Bay (Mokulei‘a Bay, Kapalua Bay and Honokeana Cove). Reef sediments and organisms (depending on their availability) were collected from each of these sites (Fig. 1). Honolua Bay is a Marine Life Conservation District and sampling of marine organisms requires a permit from the Division of Aquatic Resources (DAR). Permits were issued for collections of the alga *Halimeda kanaloana*, the goatfish *Parupeneus multifasciatus* and the urchin *Tripneustes gratilla*, but not for corals. Indeed these organisms are proposed as potential bioindicator species since they respond to most of the criteria that should be met by a bioindicator species. They are widely distributed in the West coast of Maui, available all year long and easy to collect (e.g. Moore 1966, Phillips 1990, Warnau et al. 1998). In addition since the selected organisms represent different trophic levels, the combination of data from these different organisms allow for a broader assessment of the bioavailability of metals and metalloid present in the marine environment.

2.2.1. Sampling of marine organisms and sediments

All organisms were collected between September 12 - 23, 2007. *H. kanaloana* was collected from Honolua Bay and Honokeana Cove. Epiphytes and sediments were removed from the algae by gentle scrubbing and thorough rinsing with clean 5-µm filtered seawater. *P. multifasciatus* (n = 6; mean ± S.D.: length: 24.2 ± 1.7 cm) were collected in Honolua Bay by spear fishing and samples of liver and muscle removed by dissection. *T. gratilla* between 79.7 and 84.2 mm in size were collected on snorkel from Honolua Bay, Kapalua Bay, Lipoa Point and Honokeana Cove (n = 7 per location, except for Lipoa Point n = 4). Urchins were kept alive for 24 h in plastic boxes containing 30 L of 5-µm filtered seawater (from the same sampling stations) to allow the gut contents and particulates to be excreted and shed. Sampled animals were dissected to separate gonads, intestine and body wall (including spines). The tissues sampled from each organism were weighed (wet wt), dried at 60 °C until the weight was constant, and then re-weighed (dry wt). Dried biological samples were hermetically sealed in PET containers until analyzed for metal and metalloid contents.

Superficial sediments (50 - 100 g, n = 5 replicates) were collected from all 6 sampling locations along the West coast of Maui (Fig. 1). These were placed in acid-washed PET bags and frozen (-20°C) until analyzed. Each sample was dried at 60 °C until the weight was constant, (5 d), sieved (4-mm mesh size) to eliminate stones and fragment of corals, ground using a mortar and pestle and stored in acid-washed and hermetically sealed in PET containers until analyzed for metal and metalloid contents.

2.2.2. Analyses

As, Co, Cr, Cu, Mn, Ni, Pb, V and Zn were analyzed by the Agricultural Diagnostic Service Center, at the University of Hawai‘i. Aliquots of biological samples (0.5 g) and sediment samples (0.5 g) were digested with 5 ml of 65 % HNO_3 (Merck, suprapur quality). Concentrations of metals were determined using Atom San 16 ICP (Thermo Jarrell Ash Corporation, Franklin, MA). Two control samples (one Certified Reference Materials -CRM- lobster hepatopancreas TORT-2 (NRCC) and one blank) treated and analyzed in the same way as the samples were included in each analytical batch. The results for CRM indicated recoveries ranging from 86 % (Cu) to 115 % (Pb). Mean element concentrations were given on a dry weight basis (µg g^{-1} dwt).

2.2.3. Statistical analyses

Comparisons of the data were performed using one- or two-way analysis of variance (ANOVA) followed by the multiple comparison test of Tukey (Zar 1996). Two-way ANOVA was used with sampling location and body compartment as fixed factors. The variability explained by each factor and their interactions were derived from the sum of squares (Zar 1996). The correlation and statistical significance of the relationship between the metal concentrations in sediments and those in different body compartments of the urchin *P. lividus* were evaluated using Pearson's correlation coefficient with the software R (Hornik 2010). The level of significance for statistical analyses was set at $\alpha = 0.05$.

2.3. Coral ecology survey

Ecological surveys were performed at the four stations in Honolua Bay (depth ranging from 1.5 to 2.5 m) to evaluate whether any traits in the coral ecology were correlated with the gradient of metal and metalloid concentrations observed in sediments, (Fig. 1). Six 20 m long transects were deployed randomly at each station and sampled using a line-intercept method (Hill and Wilkinson 2004). Percent cover was estimated by dividing the substrate into 6 categories: boulder bottom, reef bed, sand, alga, dead coral, and live coral. Individual coral colonies under each transect were identified to species and the size of the colony approximated by measuring maximum length, width and height. The condition of the colony was assessed for partial mortality as defined as percentage of the surface area of the colony that was dead. Colonies were also assigned to a category based on color. The color categories used were healthy, bleached, partially bleached and pale. Corals classified as healthy showed no signs of tissues discoloration; bleached coral colonies were totally white; partially bleached corals had patches of fully white tissues interspersed within the darker colored healthy tissues; and pale corals were globally paler in color than healthy colonies of the same species. Hobo® data loggers were deployed at each station (1.5 to 2.5 m depth) to record temperature and light over 6 d at a sampling interval of 15 min. Seawater samples (1500 ml, n = 3 per station) were collected on September 17th, 18th and 19th, 2007 and filtered through GF/C filter to estimate the turbidity of seawater (mg l^{-1}).

The coral cover was compared among stations using one-way ANOVA and appropriate post-hoc multiple range tests. Relationships between ecological parameters, environmental variables and sediment associated metal and metalloid concentrations were examined using correlation

(Spearman) and linear regression analysis using average values for whole station reefs using SPSS® statistical software 16.0 (SPSS Inc., Chicago, IL, USA).

3. RESULTS

3.1. Sediments

3.1.1. Honolua Bay

The four stations in Honolua Bay can be ranked according to their degree of contamination Hon1 > Hon3 > Hon2 > Hon4 with Hon1 being the most contaminated by all elements except Cu and Fe, and Hon4 the least (Table 1). Statistical analyses of the data are presented in Figure 2-A1. Results indicate that the concentrations of Co, Mn, Ni, V and Zn in sediments were significantly different among all stations. Concentrations of Cr and Cu were similar at Hon1 and Hon3, and at Hon2 and Hon4, respectively. No significant differences were observed for the Fe concentrations in sediments at Hon1, Hon2 and Hon3. There was no significant difference in the concentration of Pb measured in sediments at the four stations. For As, no significant difference was observed in sediments between station Hon1 and Hon3, and Hon1 and Hon2.

3.1.2. Honolua Bay and other adjacent Bays

One-way ANOVA was performed on element concentration measured in sediments collected from the different bays in the West Maui. For Honolua Bay, Hon1 and Hon4 were chosen for the statistical analyses because they have the broadest range of contamination (Fig. 2-A1). Sediments collected at Honokohau Bay were more contaminated than those collected from the other bays surrounding Honolua Bay and the concentrations of contaminants were in the range of those measured in the most contaminated stations of Honolua Bay (Hon1 and Hon3, Table 1). For example, Ni concentrations were 374 µg g^{-1} dwt and 303 - 481 µg g^{-1} dwt in Honokohau Bay and Honolua Bay (Hon1 and Hon3), respectively. In addition, statistical analyses (Fig. 2-A2) indicate that the concentrations of most contaminants measured in sediments from Hon1 and Honokohau Bay were generally higher than those measured in sediments from other bays, and that concentrations of Co, Fe, Mn, V and Zn measured in sediments from Hon1 and Honokohau Bay were not significantly different from one another. In contrast, metal and metalloid concentrations measured in sediments from Hon4, Lipoa Point, Kapalua Bay and Honokeana Cove were similar and lower than Honokokau Bay and Honolua sites Hon1 and Hon3. No significant difference was observed for Co, Cr, Cu, Ni, Pb, V and Zn among sediments from Hon4, Lipoa Point and Kapalua Bay.

3.1.3. Sediment Quality Guidelines

Element concentrations in sediments from all stations were compared to the NOAA Sediment Quality Guidelines (Long et al. 1995, NOAA 1999) that were developed to define the concentrations of metals and metalloid that have adverse effects on biological organisms. Within this framework, the Threshold Effect Level (TEL) represents the concentration below which adverse effects rarely occur; the Effect Range-Low (ERL) corresponds to concentration above which negative effects are more common, and the Effect Range-Median (ERM) corresponds to concentrations at or above which negative effects frequently occur. Results of the comparison are presented in Table 1.

3.2. Reef biota

Except for Fe ($p_{Tukey} < 0.05$) and Mn ($p_{Tukey} < 0.01$) there was no significant difference in the element concentrations measured in the alga *H. kanaloana* collected from Honokeana Cove and Honolua Bay (Table 2).

Concentrations of Co, Cu, Fe, Mn, and Zn measured in the livers of the goatfish *P. multifasciatus* were one to two orders of magnitude higher than in the muscle (Table 2). Very high Fe concentrations were recorded in goatfish livers reaching 4,400 µg g^{-1} dwt compared to

<16 µg g^{-1} dwt in muscle. Since individuals of *P. multifasciatus* were all collected from Honolua Bay, it was not possible to compare concentrations measured with other geographical areas.

The element concentrations measured in the gonads, intestines and body wall of the urchin *T. gratilla* collected from stations inside and outside Honolua Bay are presented in Table 2. Statistical analyses performed on the element concentrations in urchins collected from stations inside Honolua Bay (Hon1 and Hon4) and in Honokeana Cove, Lipoa Point and Kapalua Bay indicated that body compartment explained the majority of the variability for As, Cu, Fe, V, and Zn (accounting for 52 to 89 % of the global variance). Sampling station explained 40 % of the variability for Mn and 23 to 30 % of the variability observed for Cr and Cu, respectively. For Co, Cr, Cu, Ni, Pb, and Zn, an important part of the variation was associated with the residual term, ranging from 28 to 49 %, indicating that other, non-investigated factors (biological and/or environmental factors) were also influencing element concentrations in these urchin tissues. Multiple comparison tests on the mean concentrations of elements in each sampling location (all body compartments together) indicated that the concentrations of As, Co, and Mn were significantly higher ($p_{Tukey} < 0.05$) in urchins from station Hon1 compared to those from the four other stations (Fig. 2-B1). Cr and Cu concentrations in urchins from station Hon4 were significantly higher ($p_{Tukey} < 0.05$) than those measured in urchins from Honokeana Cove. Ni concentrations in urchins from Hon1 and Hon4 were not significantly different, but significantly higher than those from urchins collected at Honokeana Cove and Kapalua Bay ($p_{Tukey} < 0.05$). No significant difference was observed for Zn concentrations in urchins from the five stations. Multiple comparison tests on the mean concentrations in each body compartment (all sampling locations together) indicated that the concentrations of As, Co, Cu, Fe, Mn and Ni were significantly higher ($p_{Tukey} < 0.01$, except for Co $p_{Tukey} = 0.05$) in the intestine than in the other body compartments (Fig. 2-B2). Zn concentrations in intestine and gonads were not significantly different, but significantly higher ($p_{Tukey} < 0.0001$) than those in body wall. Cr, Pb and V concentrations were significantly higher ($p_{Tukey} < 0.0001$) in the body wall compared to the other body compartments.

Concentrations of As, Co, Fe and Mn in intestine, showed significant positive correlations with their respective concentrations in sediments (Pearson coefficient from 0.51 to 0.80, see Fig. 3). Significant correlations were also observed for Co, Mn, Ni and Zn between concentration in urchin gonads and sediments (Pearson coefficient from 0.45 to 0.78, Fig. 3). Mn concentrations in urchin carapaces were also significantly correlated with Mn sediment concentrations (Pearson coefficient of 0.87, Fig. 3).

3.3. Ecological survey

In Honolua Bay, total live coral cover was 10.9 and 13.4 % at the two inner stations (Hon1 and Hon3, respectively) and 17.4 and 26.2 % on the two offshore stations (Hon2 and Hon4, respectively) (Fig. 4). Live coral cover was significantly lower at station Hon1 compared to Hon4 ($p_{Tukey} = 0.017$), while no significant difference was observed among the other stations. Data from the ecological survey clearly indicated the presence of two types of stations in the bay. Stations Hon1 and Hon3 were characterized by a high percentage of boulder bottom (from 64 to 78 %), whereas the stations offshore were mainly composed of reef bed structure (38 to 81 %) (Fig. 4). The major species encountered in order of abundance were *Porites lobata* (percent of total number of colonies = 36.3 %), *Montipora patula* (17.7 %), *Montipora capitata* (14.6 %), *Pocillopora meandrina* (14.2 %), and *Porites compressa* (6.6 %) (Fig. 4). These five species were present at all four stations in Honolua Bay, except *P. compressa*, which was absent from Hon1. Other coral species were present but at low abundances (< 5 %).

Based on the color categories defined in § 2.3, corals present at station Hon2 were mainly healthy (78 %) compared to the other three stations where corals showed more pronounced signs of bleaching (56 - 77 %, Fig. 4). Statistical analyses (one-way ANOVA) were performed on the diameter of colony, partial mortality and the proportion of the colony that was bleached (Pale, Bleach and Partially Bleach) (after arcsin(√x) transformation) for the five most abundant coral species present in Honolua Bay (*P. lobata*, *M. patula*, *M. capitata*, *P. meandrina* and *P compressa*). Results indicated that there was no significant difference in the colony diameters and partial mortality among stations except for *P. lobata*. Colonies of *P. lobata* had a significantly higher diameter at station Hon4 as compared to the three other stations (Hon4 > Hon2 = Hon3 = Hon1; $p_{Tukey} < 0.002$), and a higher percentage of partial mortality (Hon4 = Hon2 > Hon3 = Hon1; $p_{Tukey} < 0.05$).

Results of the correlation matrices performed on the different ecological parameters and environmental conditions (element concentrations) indicated that total live coral cover was negatively correlated with Co, Cr, Mn, Ni, V, and Zn concentration in sediments (-0.955 to -0.979, $p_{Pearson} < 0.05$, Table 3), but significant linear regressions were only observed for Co and V (Fig. 5). In addition, for the coral *P. compressa*, partial mortality was correlated positively to the diameter of the colony (0.568, $p_{Pearson} < 0.05$).

The turbidity measured in Honolua Bay ranged from 14.5 (Hon4) to 68.2 (Hon1) mg l^{-1}. No significant difference was observed among the four stations in Honolua Bay on September 17 and 19, 2007, whereas the turbidity at Hon1 on September 18, 2007 was significantly higher by a factor of 3.8 compared to the other three stations in the bay (Fig. 6). Seawater temperature in Honolua Bay ranged from 26.2 to 28.5 °C and no difference was observed among the four selected stations. The salinity of seawater measured at the surface and 1.50 m depth ranged from

36.2 to 36.9 parts per thousand (ppt) except for September 18, 2007, when a rain event occurred. At the latter date, salinity of seawater decreased to 18.2 ppt at the Hon1, and a slight decrease of salinity was also observed at the three other stations (32.1 to 35.6 ppt) compared to the other sampling times (September 17 and 19, 2007).

4. DISCUSSION

Sediments are sinks for contaminants (Salomons et al. 1987), therefore the measurement of metal and metalloid concentrations in reef sediments provides basic and essential information on the degree of contamination of the reef environment. Element concentrations measured in sediments collected from Honolua Bay displayed a very wide range of concentrations, from 2.71 µg g^{-1} dwt for Co up to 7,023 µg g^{-1} dwt for Fe. Most interestingly, some elements such as Co, Cr, Mn, Ni and V reached very high concentration (e.g. up to 481 µg g^{-1} dwt for Ni). A recent study has confirmed that the concentration of Co, Cr, Mn, Ni and V in reef sediments from Honolua Bay are elevated when compared to two other watersheds in Hawaii (SE Moloka‘i and Kane‘ohe Bay) (Hédouin et al. 2009). In addition, among the four stations investigated, a clear gradient of element concentrations was observed, suggesting that the degree of contamination present in Honolua Bay is related to the discharge of sediments from Honolua Stream. To better understand the source of the elevated concentrations of metal and metalloid contamination in Honolua Bay, we investigated element concentrations in sediments from bays surrounding Honolua Bay. Concentrations of all elements measured in sediments collected at Honokohau Bay, located to the North of Honolua Bay, were very similar to the concentrations of contaminants measured in the most contaminated stations in Honolua Bay, Hon1 and Hon3, (e.g. 376 - 594 *vs.* 492 µg Mn g^{-1} dwt, 303 - 481 *vs.* 374 µg Ni g^{-1} dwt, for Honolua Bay - Hon1 and Hon3- and Honokohau Bay, respectively). Comparison of As, Cr, Cu, Ni, Pb concentrations in sediments from Honolua Bay and/or Honokohau Bay with Sediment Quality Guidelines (NOAA 1999) indicate that Cr, Ni, and Pb are in high enough concentration to elicit negative effects on biota. The similarity observed in element concentrations of sediments from both bays suggests that these bays may be contaminated by the same source. Interestingly, a ditch (Honokohau ditch) was built in 1904 to divert the flow of the Honokohau stream for off-stream uses (Fontaine 2003). The Honokohau ditch is 2.9 km long and links Honolua Bay and Honokohau Bay. This connection may explain why the metal concentrations observed in sediments of the two bays are so similar. Honolua and Honokohau watersheds are mainly forested (69 and 83 %, respectively; Parham et al. 2008), and support few anthropogenic activities. This indicates that the elevated concentrations of Co, Cr, Mn, Ni, V and Zn reflect the geology of the area and stem from high natural background in both Honolua and Honokohau watersheds as suggested by Hédouin et al. (2009) for Honolua Bay.

Regardless of the origin of the high concentrations of metals observed in sediments of Honolua Bay, the question is whether the contaminants are bioavailable and are adversely affecting the health of reef biota. Ni bound in the lattice of naturally occurring silicate minerals (e.g., olivine or pyroxenes) is less available for uptake by marine organisms as compared to water-soluble forms (CEPA 1994). That said, it is extremely difficult to predict how sediment-bound metals bioaccumulate in aquatic organisms in any given location because their bioavailability depends on their mineralogical origin (Kabata-Pendias 2001), characteristics of the sediments such as pH, oxidation-reduction potential, ionic strength, type, and concentration of organic and inorganic ligands (e.g. Callahan et al. 1979, Snodgrass 1980), and biological and physiological traits of the organism (e.g. species, age, sexual cycle, Boyden 1977, Cossa et al. 1979, Eisler 1981).

In this context, the measurement of elements in reef organisms from different trophic levels (alga, fish, urchins) collected from Honolua Bay and surrounding bays provides a snapshot view of the bioavailability of metals and a metalloid from the various sampling stations. The alga *H. kanaloana* was chosen to investigate the metal bioaccumulation in Honolua Bay because it is abundant in these areas and *Halimeda* species are generally efficient bioaccumulators of metals (Al-Shwafi and Rushdi 2008). Comparison of metal and metalloid concentrations measured in alga from Honolua Bay and Honokeana Cove indicated that while the sediments in these bays are characterized by very different degrees of contamination, with the exception for Fe and Mn, element concentrations in alga were low and similar between sites, and in the same range of concentrations reported in the literature for *Halimeda* species (see Table 4). These results suggest that either there are low concentrations of dissolved metals in Honolua Bay (with the exception of Mn and Fe) or this species of *Halimeda* does not bioaccumulate metals efficiently. The concentrations of contaminants in the goatfish *P. multifasciatus* from Honolua Bay are also low and similar to those measured in other non-contaminated areas (e.g. Mauritania coast, Manila, French Frigate Shoals -Hawai‘i- see Table 4), supporting the conclusion that the contaminants in sediments from Honolua Bay are not bioavailable to this fish species.

The urchin *T. gratilla* collected in Honolua Bay had higher concentrations of As, Co, Cr, Cu, Mn and Ni than those from less contaminated stations along the West Coast of Maui (e.g. Honokeana Cove, Kapalua Bay). However, while a clear gradient of As, Co, Cr, Cu and Ni contamination was observed in sediments, the trend was less pronounced in urchin tissues (and non-existent for algae) and significant correlations between metal concentrations in sediments and those in the urchins *T. gratilla* were only observed for some metals (e.g. Co, Mn, Ni) and for certain urchin body compartments. For example, Ni concentration in sediments collected inside

Honolua Bay were up to 48 times higher than those measured in sediments outside the bay, whereas Ni concentration measured in urchin intestines from the same stations only differed by a factor of 4. However, compared to the elevated concentrations of Ni reported in sediments from Honolua Bay (up to 481 µ g^{-1} dry wt at Hon1), the Ni concentrations reported in urchin tissues (< 2.9 µg g^{-1} dwt), and alga (< 3.9 µg g^{-1} dwt) were low. These concentrations are also low compared to concentrations of Ni measured in reef organisms living in areas highly impacted by Ni mining. For example, in the New Caledonia lagoon, concentrations of Ni reached 99.7 µg Ni g^{-1} dwt in the digestive gland of the clam *Gafrarium tumidum* in a site with 797 µg g^{-1} dwt of Ni in sediments (Hédouin et al. 2008a) and 125 µg Ni g^{-1} dwt in the alga *Lobophora variegata* living in a site with 900 µg g^{-1} dwt of Ni in sediments (Hédouin et al. 2008a, Hédouin et al. 2008b). These studies demonstrate that high Ni concentrations are measurable in marine tropical organisms when Ni is present in a bioavailable form. As such, data presented for the reef organisms in Honolua Bay collectively suggest that despite high concentration of Ni in sediments of Honolua Bay, Ni is bound in the sediments in a chemically inert form that is not bioavailable for the selected reef organisms in the present study.

In contrast to Ni, Mn concentrations were found in relatively equal proportions in the reef sediments and urchins, as confirmed by the significant correlations observed between Mn concentrations in sediments and the three body compartments of the urchins *T. gratilla*. For example, Mn concentrations were 7 times higher in sediments sampled at Hon1 than at Hon4, and 3.8 (tissues) to 7 (body wall) times higher in urchins from Hon1 compared to Hon4. This suggests that Mn is bioavailable in Honolua Bay. The higher concentration of Mn in algae from Honolua Bay as compared to Honokeana Cove also supports the presence of bioavailable Mn in Honolua Bay. Mn is an essential metal involved in many metabolic processes (Simkiss and

Taylor 1981) and it is highly bioaccumulated in marine organisms (e.g. Howe et al. 2004). Mn is currently not included in the Sediment Quality Guidelines, probably because it is thought to have low toxicity for marine species of phytoplankton, invertebrates and fish (e.g. ranging from 1.5 mg l^{-1} (5-day EC_{50}) for the marine diatom *Ditylum brightwellii* based on growth inhibition to 300 mg l^{-1} (168-h LC_{50}) for the softshell clam *Mya arenaria*, Howe et al. 2004). However, after 7-days exposure to > 0.01 mg l^{-1} Mn, embryos of the yellow crab *Cancer anthonyi* exhibited reduced survival and hatching (Macdonald et al. 1988), suggesting that early life stages of organisms are sensitive to Mn. This metal has also been reported to induce iron deficiency in some algae, leading to inhibition of chlorophyll synthesis (e.g. blue green alga *Anacystis nidulans*, Csatorday et al. 1984; green algae *Ulothrix minuta* and *U. fimbriata*, Rousch and Sommerfeld 1999). Given that corals rely on the photosynthetic activities of endosymbiotic dinoflagellates for nutrition, the impact of Mn on their biology could have a very negative effect. Further studies are needed that focus on the sensitivity of different life stages of corals to Mn to resolve the potential impact.

With the exception of Mn, the contaminants measured here displayed low bioavailability for reef biota. However, the gradient of metal concentrations observed in sediments from the four stations in Honolua Bay correlated with concentrations of sediment discharge into Honolua Bay from Honolua Stream. This provided the ecological context to examine how different levels of land-based contaminants influences the coral ecology. Interestingly, while stations located in the inner part of the bay were mainly composed of boulder bottom (64 - 78 %), corals were present at all sites, albeit with lower coral cover (10.9 and 13.4 % vs. 17.4 and 26.2 % for inshore and offshore stations, respectively), and lower species diversity (5 vs. 9 species for inshore vs. offshore stations). In addition, a shift in distribution of abundant species was also observed with the coral *Porites compressa* being more abundant in offshore than inshore stations, and *Montipora patula* more abundant in inshore than offshore stations. Although the inshore stations are rarely included in ecological survey of Honolua Bay, our results are consistent with Torricer et al. (1979), who surveyed corals in close proximity to Honolua Stream and recorded values of 1.3 to 9.5 %. Previous surveys in Honolua Bay have reported differences in coral community structure between North and South Bay. For example, *Porites* sp. dominate the north reef and sediment resistant *Montipora* sp. dominate the southern reef (Brown 2004). Interestingly, in our study, *P. lobata* was the most abundant species (32 - 39 %) in all four stations investigated. This is surprising given that *P. lobata* is reported to have a lower active sediment rejection rate than other species (Stafford-Smith 1993), and in Hawaiian Islands *P. lobata* is mainly observed in regions of moderate wave actions (Jokiel et al. 2004). These preferences are clearly reflected in the ecology of corals along the South-East fringing reef of Moloka‘i, where *P. lobata* is present in stations close to the reef crest (> 700m from shore) where sediments are mainly composed of gravel and coarse sand (38 to 93 %), but generally absent in near shore stations where sediments are fine and muddy (up to 44 % of mud) (Hédouin et al. Personal Communication, Rodgers et al. 2005). That said, *P. lobata* is sometimes found in areas with high sedimentation and/or turbidity (Australia, Ayling and Ayling 1987, Bull 1982; Pandora Reef, Palm Islands, Potts et al. 1985). Piniak (2007) recently identified a possible reason for these inconsistencies in documenting a greater negative impact on the fluorescence yield of *P. lobata* from a short-term sedimentation event (< 30 h) of 1,500 to 2,800 mg cm^{-2} composed of terrigenous sediments than the same sedimentation event with carbonate sand. These data indicate that *P. lobata,* is more sensitive to terrigenous fine particle of sediments than to coarse sand. This may explain why *P. lobata* is observed in the inner sites at Honolua Bay (Hon1 and 3), where coarse sand sediments are present (48 – 64 % of coarse sand, Hédouin et al. 2009). Finally, the coral cover in the four stations selected in Honolua Bay reflected the gradient of contaminant concentration observed in the Bay, with significant correlation observed for Co, Cr, Mn, Ni, V and Zn. However, since most of these contaminants (with the exception of Mn) are not bioavailable for the marine organisms assessed in this study, these correlations likely reflect the complex mixture of land-based contamination stressors (e.g. increasing turbidity, decreasing salinity) discharged from Honolua Stream during rainfall events (as during the event recorded on September 18th, 2008) rather than metal stress alone. In the context of the low metal bioavailability in sediments for the reef organisms, metal concentrations in sediments appears more useful as a proxy of the land-based contamination present at each site.

5. CONCLUSION

The sediments in the inshore stations in Honolua Bay displayed very high concentrations of metals and a metalloid, but the concentrations of most of these compounds measured in reef biota (alga, goatfish and urchins) are comparable to concentrations observed in non-contaminated areas (Tables 4, 5). This suggests that with the exception of Mn, the contaminants present in the marine environment of Honolua Bay exhibit low bioavailablility for reef biota. The data demonstrate that the bioavailability of metals and metalloid in Honolua Bay is different depending on the element under consideration. For example, Mn is more bioavailable than Ni even though the gradients of metal concentrations observed in sediments for these two elements were relatively similar. Nevertheless, given that the bioavailability of metals in marine organisms is influenced by physical and chemical condition such as pH and temperature, the bioavailability of these contaminants may change in the context of global warming in the future. In addition, further works should focus on assessing the bioaccumulation and effects of contaminants on

Scleractinian corals present in Honolua Bay, since the sensitivity of corals may be different from the other organisms selected in this study. The high concentration of sediment associated metal and metalloid concentrations highlight the influence of Honolua Stream in discharging sediments into Honolua Bay. Other chemical materials associated with agriculture, such as pesticides, that were not measured here are also likely to be associated with these sediments and to contribute to the complex mixture of threats facing the corals of Honolua Bay. Alleviating local stress level by reducing sediment discharges into Honolua Bay is a feasible and direct management action that has the potential to help coral reefs better face global stressors that are less easy to ameliorate. Such activity has thus the potential to contribute significantly to the conservation of coral reef ecosystem of Honolua Bay.

Acknowledgement

This work was funded by the Coral Reef Land-Based Pollution Local Action Strategy of Hawai‘i. The authors thank Dr K Chaston for her constant support and help in the field, Dr L Guidi for providing the map of West Maui, DA Gulko and the Department of Land and Natural Resources for permits, and Maui DAR personal R Sparks, KK Wong, JK Mitchell and S Hau for their help in catching the goatfishes in Honolua Bay. This work is Hawaii Institute of Marine Biology Contribution Number 3333.

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Figure 1. Selected sampling locations for reef sediments, the alga *Halimeda kanaloana*, the goatfish *Parupeneus multifasciatus* and the urchin *Tripneustes gratilla*, along the West coast of Maui, Hawaii

Figure 2. Comparisons of element concentrations in (A) sediment collected (A1) inside and (A2) inside and outside Honolua Bay, using multiple comparison test of Tukey performed after one-way ANOVA, and (B) the urchin *Tripneustes gratilla* using multiple comparison test of Tukey performed after two-way ANOVA (B1, Geographical variation; B2, Body compartment). Mean concentrations are ranked from the left to the right by decreasing order. Concentrations in underlined body compartments or stations are not significantly different ($\alpha = 0.05$).

Body compartments: *Intestinal tissues* (I), *Gonad* (G), *Body wall* (B)

Sampling locations: *Honolua 1* (Hon1), *Honolua 2* (Hon2), *Honolua 3* (Hon3), *Honolua 4* (Hon4), *Honokeana Cove* (HC), *Lipoa Point* (LP), *Kapalua Beach* (KB), *Honokohau Bay* (HB) and *Mokulei'a Bay* (MB)

Figure 3. Element concentrations in three body compartments of the urchin *Tripneustes gratilla* (intestine, gonads and carapace) as a function of their respective element concentrations in sediments. ("*" indicate that the significant correlation was observed between metal concentration in urchin body compartments and those in sediments; *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$,****$p < 0.001$)

Figure 4. Ecological parameters of four stations in Honolua Bay. (A) Percent distribution of various bottom types (Live coral, dead coral, boulder bottom, alga, sand and reef bed); (B)

Percentage (Distribution frequency) of coral colonies measured at each station; (C) Percent distribution of coral colors (Healthy; Pale, Partially bleached, Bleached); (D) Average colony diameters for the five most abundant coral species (Mean ± S.D.); (E) Percentage of mortality of the five most abundant coral species.

Species codes: *Porites lobata* (PLOB), *Porites compressa* (PCOM), *Montipora capitata* (MCAP), *Montipora patula* (MPAT), *Pocillopora meandrina* (PMEA)

Station codes: *Honolua 1* (Hon1), *Honolua 2* (Hon2), *Honolua 3* (Hon3), *Honolua 4* (Hon4)

Figure 5. Linear regressions of mean live coral cover versus metal concentration. Mean total coral cover vs. (A) Co and (B) V concentration in sediments, all stations. Coefficient of determination and significance shown only for significant regressions.

Figure 6. Turbidity (Mean ± S.D.) (A) and temperature (B) of seawater at the four stations in Honolua Bay over time. A rain event occurred on September 18th, 2007.

Station codes: *Honolua 1* (Hon1), *Honolua 2* (Hon2), *Honolua 3* (Hon3), *Honolua 4* (Hon4)

Metal and metalloid levels in sediments and tropical organisms from West Maui.
Ecological surveys of corals in Honolua Bay.
Elevated levels of Co, Cr, Mn, Ni and V in reef sediments.
Low bioavailability of contaminants for organisms.
Correlations between coral cover and Co, Cr, Mn, Ni, V, Zn levels in sediments.

Sites	As m ± S.D.	Co m ± S.D.	Cr m ± S.D.	Cu m ± S.D.	Fe m ± S.D.	Mn m ± S.D.	Ni m ± S.D.	Pb m ± S.D.	V m ± S.D.	Zn m ± S.D.
Honolua 1	39.2 ± 4.8 [b]	48.4 ± 7.3	95.9 ± 12.0 [b]	13.9 ± 2.5	7013 ± 175	594.4 ± 49.8	481.3 ± 62.1 [c]	36.2 ± 4.6 [a]	346.1 ± 48.3	54.9 ± 4.4
Honolua 2	34.3 ± 2.3 [b]	16.9 ± 2.5	40.7 ± 5.4	7.08 ± 1.34	7023 ± 171	249.8 ± 26.4	151.4 ± 34.8 [c]	19.0 ± 3.3	179.5 ± 26.3	20. ± 2.0
Honolua 3	42.5 ± 1.5 [b]	36.6 ± 1.2	93.5 ± 4.3 [b]	17.1 ± 1.3	7018 ± 172	375.8 ± 12.2	302.8 ± 16.5 [c]	34.7 ± 4.5 [a]	269.7 ± 12.9	47.8 ± 1.8
Honolua 4	24.0 ± 0.3 [b]	2.71 ± 0.4	13.9 ± 1.0	5.25 ± 0.88	3253 ± 247	84.6 ± 10.3	9.93 ± 1.35	14.6 ± 16.7	89.4 ± 10.0	6.52 ± 0.67
Hokuanui bay	34.8 ± 3.2 [b]	3.61 ± 0.61	16.7 ± 0.4	6.00 ± 0.24	5131 ± 962	135.4 ± 16.8	17.7 ± 3.7 [a]	17.6 ± 0.6	108.3 ± 7.6	10.7 ± 2.2
Honokeana cove	27.01 ± 0.4 [b]	5.41 ± 0.5	21.3 ± 1.0	7.54 ± 0.24	6828 ± 5	168.4 ± 8.9	22.6 ± 2.4 [b]	20.7 ± 0.7	103.2 ± 4.4	16.7 ± 2.5
Lipoa point	25.7 ± 0.5 [b]	2.65 ± 0.2	14.7 ± 0.9	6.09 ± 0.45	3259 ± 251	91.1 ± 11.6	10.31 ± 1.71	15.9 ± 0.8	94.4 ± 3.8	6.7 ± 0.61
Honokohau bay	56.2 ± 1.4 [b]	45.5 ± 3.2	73.1 ± 5.1 [a]	17.1 ± 1.0	7016 ± 169	491.7 ± 21.0	373.9 ± 43.9 [c]	35.3 ± 1.7 [a]	343.0 ± 27.0	51.2 ± 2.1
Mokulei'a bay	48.1 ± 1.4 [b]	19.9 ± 2.1	47.3 ± 5.7	9.39 ± 0.66	6836 ± 8	296.5 ± 15.3	144.6 ± 28.4 [c]	26.1 ± 0.9	190.6 ± 13.1	25.1 ± 2.4
TEL	7.24		52.3	18.7			15.9	30.24		124.0
ERL	8.2		81	34			20.9	46.7		150.0
ERM	70		370	270			51.6	218		410.0

Table 1. Metal and metalloid concentrations in superficial reef sediments collected from 9 sites in West Maui, and values of the Sediment Quality Guidelines. TEL: Threshold Effect Level; ERL: Effect-Range Low; ERM: Effect-Range Median based on NOAA sediment quality guideline (Long et al. 1995) and NOAA Screening Quick Reference Tables (NOAA 1999).

[a] indicated that the element concentration is superior to the TEL, [b] to the ERL, and [c] to the ERM.

Species	**Sites**	**As** m ± S.D.	**Co** m ± S.D.	**Cr** m ± S.D.	**Cu** m ± S.D.	**Fe** m ± S.D.	**Mn** m ± S.D.	**Ni** m ± S.D.	**Pb** m ± S.D.	**V** m ± S.D.	**Zn** m ± S.D.
						Gonads					
T. gratilla	Honolua 1	17.6 ± 4.7	1.41 ± 0.29	5.05 ± 1.93	3.34 ± 0.63	239 ± 121	14.2 ± 5.4	2.47 ± 1.35	6.06 ± 0.91	37.8 ± 8.3	52.8 ± 24.3
	Honolua 4	14.8 ± 4.7	1.05 ± 0.65	7.99 ± 1.88	4.53 ± 0.86	202 ± 131	3.64 ± 2.16	2.23 ± 0.57	9.16 ± 2.10	47.0 ± 15.1	25.4 ± 9.1
	Kapalua	15.1 ± 2.4	0.53 ± 0.26	2.38 ± 0.95	2.14 ± 0.83	65.4 ± 24.1	2.83 ± 2.57	0.87 ± 0.25	2.93 ± 1.95	48.0 ± 24.2	28.0 ± 23.6
	Honokeana	9.74 ± 3.43	0.70 ± 0.84	1.75 ± 0.71	2.26 ± 0.65	42.0 ± 18.0	3.89 ± 2.03	0.58 ± 0.19	3.21 ± 1.35	24.2 ± 5.2	30.7 ± 12.2
	Lipoa Point	14.6 ± 2.8	0.94 ± 0.06	2.95 ± 0.60	3.19 ± 1.11	52.9 ± 34.6	4.26 ± 2.58	0.98 ± 0.09	5.04 ± 0.33	36.1 ± 15.0	28.3 ± 12.1
						Intestine					
	Honolua 1	80.3 ± 17.8	2.33 ± 0.54	3.36 ± 0.86	7.66 ± 1.05	946 ± 163	28.9 ± 9.3	2.82 ± 0.92	6.83 ± 0.77	26.0 ± 6.1	36.3 ± 5.1
	Honolua 4	37.1 ± 5.3	1.35 ± 0.57	4.04 ± 1.77	7.30 ± 1.23	625 ± 82.4	7.54 ± 1.58	2.80 ± 0.88	7.20 ± 1.45	27.7 ± 3.9	43.2 ± 11.4
	Kapalua	38.7 ± 11.5	1.06 ± 0.08	2.50 ± 0.70	4.94 ± 1.75	738 ± 210	8.80 ± 1.00	1.60 ± 1.67	5.65 ± 0.46	35.1 ± 8.0	38.0 ± 8.7
	Honokeana	40.0 ± 6.9	0.55 ± 0.45	1.14 ± 1.17	5.96 ± 0.85	1096 ± 413	16.0 ± 5.7	1.22 ± 0.44	5.02 ± 0.59	31.7 ± 5.8	31.8 ± 3.9
	Lipoa Point	59.6 ± 19.8	1.33 ± 0.02	2.97 ± 0.34	8.86 ± 1.90	672 ± 219	12.2 ± 3.2	2.42 ± 0.93	6.91 ± 0.56	32.2 ± 2.3	43.7 ± 10.7
						Body Wall					
	Honolua 1	14.3 ± 2.8	0.85 ± 0.29	4.97 ± 2.14	3.48 ± 2.02	62.7 ± 24.7	9.03 ± 3.56	1.28 ± 0.63	6.61 ± 4.14	106.7 ± 7.7	3.28 ± 1.58
	Honolua 4	15.0 ± 3.1	0.89 ± 0.29	5.14 ± 1.46	3.37 ± 1.39	22.6 ± 11.0	1.24 ± 0.54	1.18 ± 0.53	7.86 ± 3.71	103.4 ± 9.0	2.93 ± 0.70
	Kapalua	17.5 ± 2.3	1.23 ± 0.10	6.04 ± 1.11	4.93 ± 1.20	29.9 ± 6.6	2.06 ± 0.68	1.66 ± 0.68	13.1 ± 0.6	111.9 ± 7.0	2.56 ± 0.27
	Honokeana	14.0 ± 3.2	1.09 ± 0.16	4.13 ± 1.82	2.98 ± 1.84	13.4 ± 4.3	2.57 ± .76	1.05 ± 0.31	6.05 ± 5.21	98.5 ± 7.9	2.72 ± 0.43
	Lipoa Point	14.2 ± 3.1	0.69 ± 0.76	4.05 ± 1.51	2.69 ± 1.87	10.0 ± 3.8	2.22 ± 0.73	0.80 ± 0.83	5.93 ± 4.75	104.2 ± 8.3	2.47 ± 0.65
						Muscle					
P. multifasciatus	Honolua	39.9 ± 10.7	0.17 ± 0.11	1.40 ± 0.47	0.87 ± 0.24	14.8 ± 6.5	0.56 ± 0.34	0.69 ± 0.46	1.45 ± 0.44	3.85 ± 0.86	10.3 ± 1.9
						Liver					
	Honolua	54.8 ± 27.0	1.98 ± 0.79	1.44 ± 1.05	15.6 ± 3.2	4400 ± 931	7.42 ± 1.76	0.53 ± 0.38	2.89 ± .89	5.11 ± 2.38	112 ± 10.3
H. kanaloana	Honolua 5	15.8 ± 5.6	0.92 ± 0.43	6.24 ± 2.77	4.02 ± 1.52	531 ± 155	12.8 ± 2.3	3.81 ± 1.88	8.74 ± 3.10	23.4 ± 3.4	2.63 ± 0.61
	Honokeana	16.0 ± 7.5	1.33 ± 0.68	7.32 ± 2.82	4.96 ± 2.24	374 ± 74.5	9.86 ± 0.89	1.97 ± 1.27	8.52 ± 5.22	23.2 ± 15.0	3.09 ± 1.95

Table 2. Element concentrations (mean ± S.D.; µg g^{-1} dwt) in the urchin *Tripneustes gratilla* (n = 7 per station, except for Lipoa Point n = 4), the goatfish *Parupeneus multifasciatus* (n = 6) and the alga *Halimeda kanaloana* (n = 7) collected in the West Maui

A) GENERAL		
Factor 1	**Factor 2**	**Pearson values**
Coral cover	Co	-0.972 *
Coral cover	Cr	-0.955 *
Coral cover	Mn	-0.955 *
Coral cover	Ni	-0.960 *
Coral cover	V	-0.979 *
Coral cover	Zn	-0.958 *

B) BY CORAL SPECIES			
Species	**Factor 1**	**Factor 2**	**Pearson values**
PLOB	Diameter	As	-0.964 *
PLOB	Diameter	Fe	-0.976 *
MPAT	Diameter	Cu	-0.976 *
PCOM	Diameter	Partial mortality	+0.992 **
PCOM	Diameter	Turbidity	-0.975 *

Table 3. Results of the Pearson Correlation performed on the different reef health parameters and the element concentration in sediment for A) all species combined and B) for each coral species. Only significant correlations (<0.05) are presented (*: < 0.05; **: < 0.01)

Species codes: *Porites lobata* (PLOB), *Porites compressa* (PCOM), *Montipora patula* (MPAT)

	Species	Location	As	Co	Cr	Cu	Fe	Mn	Ni	Pb	V	Zn
GOATFISH	*Mulloidichthys vanicolensis* [1,A]	French Frigate Shoals	121		7.5	30				20		273
	Pseudupeneus prayensis [2, B]	Mauritania coast				0.9 ± 0.2 - 1.6 ± 0.6						11 ± 1 - 16 ± 4
	P. prayensis [2, C]	Mauritania coast				1.6 ± 0.3 - 3.1 ± 1.3						79 ± 4 - 97 ± 18
	P. prayensis [2, D]	Mauritania coast				13.8 ± 3.1 - 18 ± 1.0						103 ± 13 - 134 ± 5
	Upenous moluccensis [3, A]	Manila bay		0.108		2.12		8.32		0.0951		66.1
ALGA	*Halimeda opuntia* [4]	Red Sea (Saudi Arabia)		0.14	0.49				0.64	2.52	0.54	
	H. tuna [5]	Suez		14.5 ± 1.4	13.4 ± 3.3	7.4 ± 1.7		27.7 ± 1.7	16.7 ± 2.9	49.8 ± 4.1		37.3 ± 3.7
	H. tuna [5]	Mars Alam		4.1 ± 1.3	3.8 ± 1.8	3.8 ± 1.0		7.3 ± 2.1	5.7 ± 1.4	8.9 ± 1.4		6.3 ± 2.1
	H. tuna [6]	Chalkidiki, Aegean Sea				4.5		71.3	21.9	0.02		14.6
	H. tuna [7]	Gulf of Aden, Yemen		0.3	3.4	8.31	60.2	3.5	4.7	3.2	0.3	2.53
	H. tuna [8]	Sea Area off Beirut				32.1	476.0		42.0	51.9		
	H. incrassata [9]	La Curieuse Island			< 1.2	< 0.6	18.98	6.28	< 1.2	< 2		7.29
	H. Taenicola [10]	Suvorov Atoll				2.86	27.62	6.43				5.95
	H. micronesica [10]	Suvorov Atoll				2.97	25.99	7.43				6.93
	H. discoidea [10]	Bio Island				3.01	45.37	6.94		3.01		10.88
	H. simulaus [10]	Bio Island				3.20	41.63	6.90		2.46		9.85

[1] Miao et al. 2001; [2] Roméo et al. 1999; [3] Prudente et al. 1997; [4] El-Naggar and Al-Amoudi 1989; [5] Abdallah et al. 2005; [6] Sawidis et al. 2001; [7] Al-Shwafi and Rushdi 2008; [8] Shiber 1980; [9] Dolgushina et al. 1995; [10] Khristoforova and Bogdanova 1980

[A] Whole, [B] Muscle, [C] Gills, [D] Liver

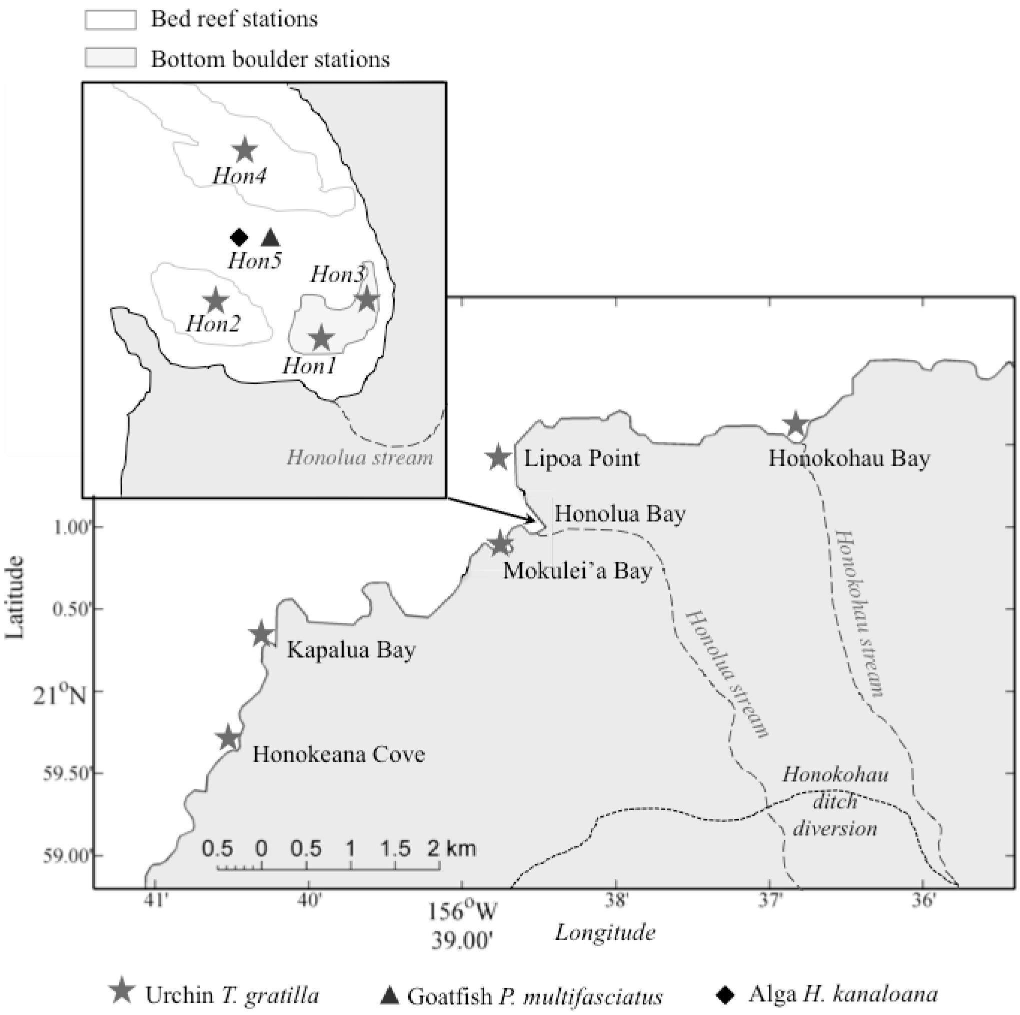
Table 4. Element concentrations (mean ± S.D. or range; μg g^{-1} dwt) in goatfishes and the algae *Halimeda* sp. from various geographical areas

Urchin species	Location	Organs	As	Cr	Cu	Fe	Mn	Ni	Pb	V	Zn
Diadema setosum [1]	Singapore reef	Gonads		1.39 ± 0.99 - 4.83 ± 3.57	2.91 ± 0.45 - 7.73 ± 7.18	88 ± 77 - 285 ± 229			0.78 ± 0.29 - 1.86 ± 0.65		129 ± 162 - 307 ± 369
D. setosum [1]	Singapore reef	Body wall		0.48 ± 0.15 - 1.11 ± 0.95	0.31 ± 0.22 - 1.65 ± 1.28	25 ± 16 - 81 ± 46			2.48 ± 0.67 - 4.24 ± 1.3		12.33 ± 1.17 - 15.14 ± 2.18
D. setosum [1]	Singapore reef	Skeleton		1.18 ± 0.76 - 2.22 ± 0.71	0.35 ± 0.12 - 1.01 ± 0.36	8 ± 3 - 34 ± 26			4.69 ± 0.85 - 7.4 ± 2.05		4.82 ± 0.6 - 6.36 ± 1.63
Echinocardium cordatum [2]	Isle of Arran, Scotland	Gonads			7	184			4,4		239
E. cordatum [2]	Isle of Arran, Scotland	Gut			11	3480			5,8		74
Echinus esculentus [3]	Irish Sea, UK	Oral body wall			1,8	6,9			<0.62		110
E. esculentus [3]	Irish Sea, UK	Aboral body wall			0,9	2,5			<0.62		12
E. esculentus [3]	Irish Sea, UK	Gonads			16	15			<0.68		110
Echinometra lucunter [4]	Cuba	Gonads			2.57 - 6.09	45.8 - 180					230 - 436
Paracentrotus lividus [5]	Marseille (France)	Body wall			1 - 5.33				0.3 - 1.19		
P. lividus [5]	Marseille (France)	Gonads			4.02 - 6.34				0.3 - 3.14		
P. lividus [6]	NW Mediterranean	Gonads		0.88 - 1.59	2.68 - 3.18	35 - 101			1.38 - 2.02		124 - 161
P. lividus [5]	Marseille (France)	Gonads			6,34				3,14		
P. lividus [5]	Marseille (France)	Gut			22,9				28,1		
P. lividus [6]	NW Mediterranean	Digestive wall		0.86 ± 0.17 - 1.23 ± 0.75	22 ± 6 - 27 ± 7	120 ± 58 - 287 ± 159			1.93 ± 0.56 - 2.12 ± 1.32		70 ± 14 - 80 ± 12
P. lividus [6]	NW Mediterranean	Gonads		0.88 ± 0.34 - 1.59 ± 0.92	2.68 ± 0.94 - 3.18 ± 0.90	35 ± 17 - 101 ± 62			1.38 ± 0.70 - 2.02 ± 1.06		124 ± 111 - 161 ± 192
P. lividus [6]	NW Mediterranean	Body wall		0.73 ± 0.64 - 0.89 ± 0.77	0.49 ± 0.18 - 0.65 ± 0.28	4.37 ± 2.01 - 13.7 ± 8.7			3.68 ± 2.94 - 5.39 ± 3.50		3.84 ± 0.78 - 5.21 ± 1.34
P. lividus [7]	NW Mediterranean	Digestive wall		0.78 ± 0.12 - 1.74 ± 1.54	14.1 ± 4.7 - 31.1 ± 7.3	66 ± 7 - 320 ± 166			1.24 ± 0.51 - 4.90 ± 0.72		54 ± 10 - 88 ± 16
P. lividus [7]	NW Mediterranean	Gonads		0.67 ± 0.20 - 2.16 ± 1.13	1.03 ± 0.57 - 3.83 ± 0.59	23 ± 9 - 119 ± 66			0.74 ± 0.17 - 3.02 ± 1.31		53 ± 51 - 383 ± 253
P. lividus [7]	NW Mediterranean	Body wall		0.24 ± 0.05 - 2.05 ± 0.15	0.19 ± 0.13 - 0.86 ± 0.12	3.28 ± 1.30 - 17.9 ± 14.3			1.48 ± 0.55 - 7.76 ± 0.83		3.08 ± 0.85 - 6.28 ± 1.45
P. lividus [8]	Balearic Islands	Full body tissues	0.7–4.1	0.4–3.2	1.6–7.5			0.8–2.7	0.8–6.7		5.7–74.5
P. lividus [9]	Southern Adriatic Sea	Gonads			5.19 ± 2.68	184 ± 166			0.86 ± 0.67		157.13 ± 47.91
Strongulocentrotus intermedius and nudus [10]	Amursky bay (Russia)	Gonads			0,8	147					28,5
S. droebachiensis [11]	Artic bay	Whole	3.5 ± 0.6 - 3.9 ± 0.9		2.9 ± 0.5 – 3.2 ± 0.5	495 ± 300 - 1310 ± 570					34 ± 5.8 - 57 ± 17
S. droebachiensis [11]	Artic bay	Gonads	11 ± 4.9		5.2 ± 3.3	217 ± 58					153 ± 50
Sphrerechinus granularis [12]	Brest Bay	Gonads			3.7 - 5	189 - 320			0.79 - 1.14		476.4 - 706.3
S. granularis [12]	Brest Bay	Gut			9.95 - 12.9	4057 - 4601			3.2 - 3.6		128.4 - 220.2
Sterechinus neumayeri [13]	King George Islands	Body wall	0.04 ± 0.01	21.0 ± 11	7.0 ± 4.0	5400 ± 3200	100 ± 50	4.0 ± 2.0	10.0 ± 6.0	19 ± 12	260 ± 60
S. neumayeri [13]	King George Islands	Digestive tract	0.05 ± 0.05	23.0 ± 12.0	1.0 ± 0.2	300 ± 100	9 ± 2	2.0 ± 1.0	1.0 ± 0.4	9 ± 1	100 ± 20
S. neumayeri [13]	Deception Island	Body wall	1.0 ± 1.0	100 ± 53	0.2 ± 0.1	2400 ± 1000	100 ± 30	4.0 ± 2.0	13.0 ± 5.0	10 ± 4	620.0 ± 136.0

[1] Flammang et al. 1997; [2] Buchanan et al. 1980; [3] Riley and Segar 1970; [4] Ablanedo et al. 1990; [5] Augier et al. 1989; [6] Warnau et al. 1995; [7] Warnau et al. 1998; [8] Deudero et al. 2007; [9] ;Storelli et al. 2001; [10] Naidenko 1997; [11] Bohn 1979; [12] Guillou et al. 2000; [13] Deheyn et al. 2005;

Table 5. Element concentrations (mean ± S.D. or range; μg g^{-1} dwt) in urchins from various geographical areas

Figure 1



Geographical coordinates of the stations:

Hon1 (N21°00.822, W156°38.332)	Hon2 (N21°00.835, W156°38.405)
Hon3 (N21°00.844, W156°38.277)	Hon4 (N21°00.913, W156°38.313)
Hon5 (N21°00.849, W156°38.297)	Mokulei'a Bay (N21°00.747, W156°38.517)
Kapalua Bay (N21°00.046, 156°40.057)	Honokeana Cove (N20°59.508, W156°40.124)
Lipoa Point (N21°01.046, W156°38.419)	Honokohau Bay (N21°01.324, W156°36.563)

Figure 2

A- Superficial sediments

A-1

Metal	Location ranking			
As	Hon3	Hon1	Hon2	Hon4
Cd	Hon1	Hon3	Hon2	Hon4
Co	Hon1	Hon3	Hon2	Hon4
Cr	Hon1	Hon3	Hon2	Hon4
Cu	Hon3	Hon1	Hon2	Hon4
Fe	Hon2	Hon3	Hon2	Hon4
Mn	Hon1	Hon3	Hon2	Hon4
Ni	Hon1	Hon3	Hon2	Hon4
Pb	Hon1	Hon3	Hon2	Hon4
V	Hon1	Hon3	Hon2	Hon4
Zn	Hon1	Hon3	Hon2	Hon4

A-2

Metal	Location ranking						
As	HB	MB	Hon1	KB	HC	LP	Hon4
Cd	Hon1	HB	MB	HC	KB	LP	Hon4
Co	Hon1	HB	MB	HC	KB	Hon4	LP
Cr	Hon1	HB	MB	HC	KB	LP	Hon4
Cu	HB	Hon1	MB	HC	LP	KB	Hon4
Fe	HB	Hon1	MB	HC	KB	LP	Hon4
Mn	Hon1	HB	MB	HC	KB	LP	Hon4
Ni	Hon1	HB	MB	HC	KB	LP	Hon4
Pb	Hon1	HB	MB	HC	KB	LP	Hon4
V	Hon1	HB	MB	KB	HC	LP	Hon4
Zn	Hon1	HB	MB	HC	KB	LP	Hon4

B- Urchin *T. gratilla*

B-1

Metal	Location ranking				
As	Hon1	KB	Hon4	LP	HC
Cd	LP	HC	Hon4	Hon1	KB
Co	Hon1	Hon4	LP	HC	KB
Cr	Hon4	Hon1	LP	KB	HC
Cu	Hon4	Hon1	LP	HC	KB
Fe	Hon1	Hon4	KB	LP	HC
Mn	Hon1	LP	HC	KB	Hon4
Ni	Hon1	Hon4	LP	KB	HC
Pb	Hon4	Hon1	LP	HC	KB
V	KB	Hon4	Hon1	LP	HC
Zn	KB	Hon4	Hon1	LP	HC

B-2

Metal	Compartment ranking		
As	I	G	C
Cd	I	G	C
Co	I	G	C
Cr	C	G	I
Cu	I	G	C
Fe	I	G	C
Mn	I	G	C
Ni	I	G	C
Pb	C	I	G
V	C	G	I
Zn	I	G	C

Figure 3

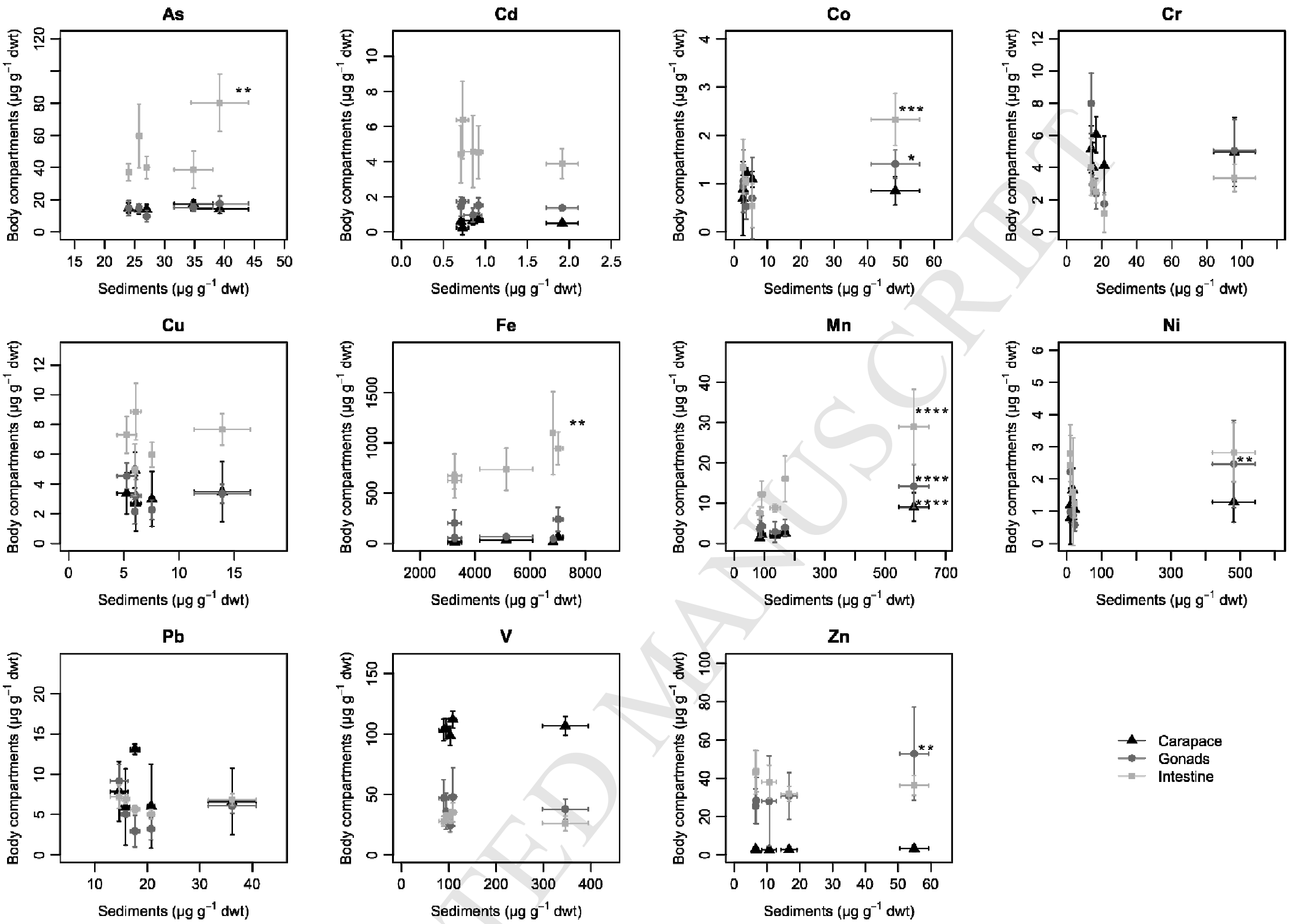

As
Cd
Co
Cr
Cu
Fe
Mn
Ni
Pb
V
Zn
Body compartments (μg g−1 dwt)
Sediments (μg g−1 dwt)
Carapace
Gonads
Intestine

Figure 4

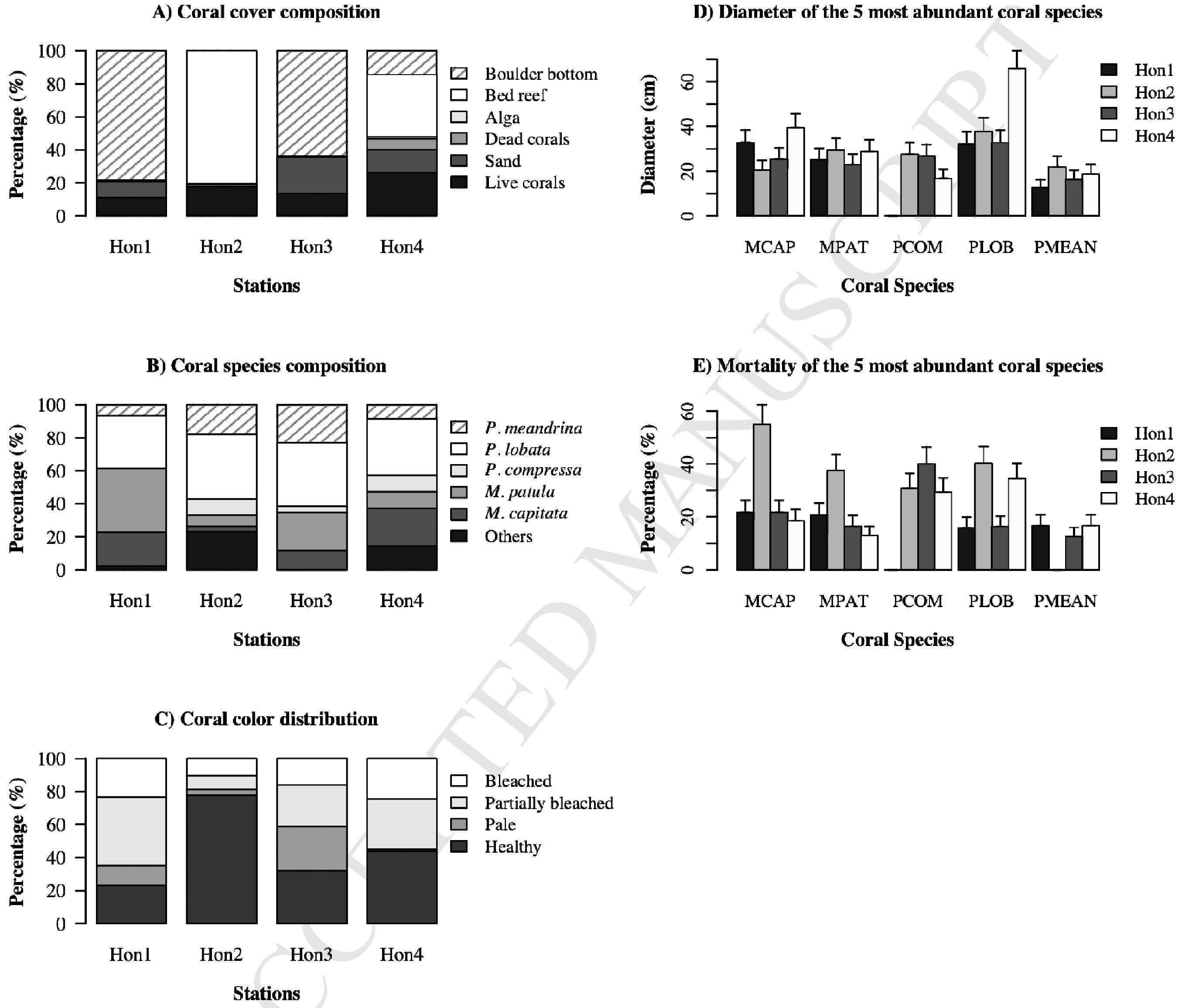

A) Coral cover composition
Percentage (%)
Boulder bottom
Bed reef
Alga
Dead corals
Sand
Live corals
Hon1
Hon2
Hon3
Hon4
Stations
D) Diameter of the 5 most abundant coral species
Diameter (cm)
MCAP
MPAT
PCOM
PLOB
PMEAN
Coral Species
B) Coral species composition
P. meandrina
P. lobata
P. compressa
M. patula
M. capitata
Others
E) Mortality of the 5 most abundant coral species
C) Coral color distribution
Bleached
Partially bleached
Pale
Healthy

Figure 5

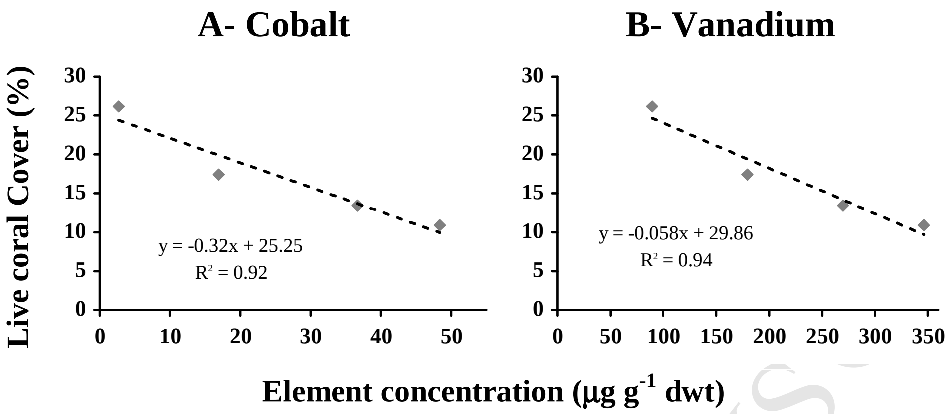
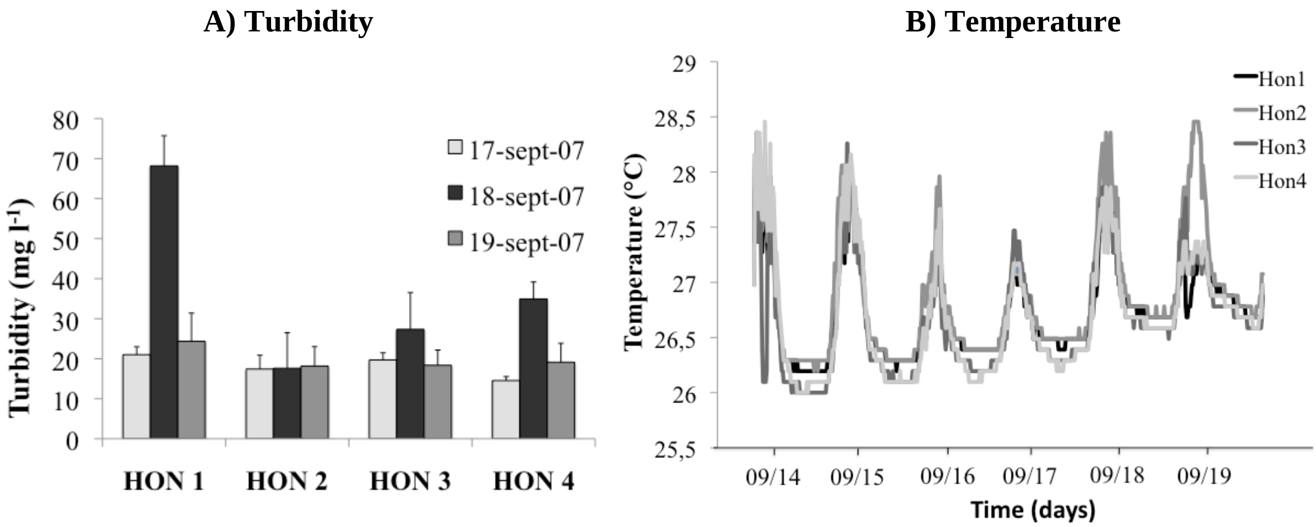

A- Cobalt
B- Vanadium
Live coral Cover (%)
30
25
20
15
10
5
0
0
10
20
30
40
50
y = -0.32x + 25.25
R² = 0.92
0
50
100
150
200
250
300
350
y = -0.058x + 29.86
R² = 0.94
Element concentration (µg g-1 dwt)

Figure 6


A) Turbidity
Turbidity (mg l-1)
0
10
20
30
40
50
60
70
80
17-sept-07
18-sept-07
19-sept-07
HON 1
HON 2
HON 3
HON 4
B) Temperature
Temperature (°C)
25,5
26
26,5
27
27,5
28
28,5
29
Hon1
Hon2
Hon3
Hon4
09/14
09/15
09/16
09/17
09/18
09/19
Time (days)