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Comparison of metal accumulation in the azooxanthellate scleractinian coral (*Tubastraea coccinea*) from different polluted environments

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ABSTRACT

The response of metal accumulation in coral *Tubastraea coccinea* to various degrees of metal enrichment was investigated from the Yin-Yang Sea (YYS) receiving abandoned mining effluents, the Kueishan Islet (KI) hydrothermal vent field, and the nearshore area of remoted Green Island (GI). The concentrations of most dissolved metals were highest in seawater at YYS, followed by KI, and then GI, showing the effects of anthropogenic and venting inputs on metal levels. Five metals (Co, Fe, Mn, Ni, and Zn) yielded significant differences ($p < 0.05$) among the skeleton samples. We identified similar patterns in the metal–Ca ratios, indicating that the elevated metals in skeletons was a consequence of external inputs. The coral tissues were relatively sensitive in monitoring metal accumulation, showing significant differences among three locations for Cd, Co, Cu, Fe, Pb, Ni, and Zn. Specific bioconcentration factors provided strong support for the differential metal accumulation in skeletons and tissues.

1. Introduction

The coral reefs of tropical regions worldwide are affected by diminished biodiversity and various stressors in coastal environments. The terrestrial runoff of nutrients, pollutants, and sediments, as well as global warming and ocean acidification are all major contributors to the catastrophic decline of coral abundance and diversity (Ferrier-Pages et al., 2000; Hughes et al., 2003; Selkoe et al., 2008; Wolanski et al., 2008; Takesue et al., 2009; Tseng et al., 2011; Chan et al., 2012). Numerous previous studies have identified terrestrial and marine pollution as the primary factor in causing the deterioration of coral reef ecosystems (Brown and Howard, 1985; Shieh and Duedall, 1992; Richmond, 1993; Brodie et al., 2012). Therefore, with continuous changes in the marine environments, most studies have examined the accumulation of heavy metals in coral tissues and skeletons to determine the long-term effects of environmental factors in addition to direct anthropogenic inputs (Shen and Boyle, 1988; Esslemont et al., 2000). Although the majority of coral reef ecosystems have been regarded as pristine environments, previous studies have shown that the marine pollution associated with river discharge and effluents from mining sites have affected coral reefs in several regions around the world (Brown and Howard, 1985; Scott, 1990; Shieh and Duedall, 1992; Richmond, 1993; Brodie et al., 2012). Thus, the determination of metal accumulation in coral tissues and skeletons could be useful in examining environmental changes and pollution (Howard and Brown, 1986; Shen and Boyle, 1987; Esslemont, 2000; Hoffmann, 2002).

Previous analyses of metals present in coral tissues and skeletons were able to assess metal loads because corals can uptake metals directly either from seawater or through coral feeding (Chan et al., 2012). The abundance of scleractinian coral *Tubastraea coccinea* situated in proximity to Taiwan's coastal seas are produced from a single polyp (Ladd, 1961) (Fig. 1). Previous experiments have shown that the uptake of elements by corals from seawater contains both $^{45}Ca^{++}$ and $H^{14}CO_3$. Calcium is therefore deposited into the $CaCO_3$ skeletons and ^{14}C is fixed to the tissues as organic matter and into the skeletons as $^{14}CO_3$ (Goreau and Goreau, 1960; Ladd, 1961). Hence, coral tissues and $CaCO_3$ skeletons record and preserve changes in the chemical composition of seawater (Prouty et al., 2008). There are various mechanisms that can cause the deposition of metals into corals, such as (a) substitution of dissolved metal ions into the crystal lattice through Ca substitution, (b) trapping particulate matter

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Fig. 1. The identification of *T. coccinea* at YYS, KI and GI sampling locations.

within skeleton cavities, and (c) uptaking organic matter either from the coral tissue or through coral feeding (Howard and Brown, 1986; Hanna and Muir, 1990; Brown et al., 1991). The calcification of coral skeleton extension rates could also have a critical role in modulating the metal assimilation between metal exposure in seawater and metal accumulation in coral $CaCO_3$ skeletons; therefore, the coral age and body size could have a substantial effect on reconstructing natural and anthropogenic changes in reef environments.

In this study, we hypothesize that the accumulation of various metals in coral *T. coccinea* (Lesson, 1829) would vary among different polluted environments. Thus, the objectives of this study were to (a) determine the levels of dissolved metals in seawater, (b) determine the bioaccumulation of metals in skeletons and tissues of the coral samples from three locations, and (c) assess the relationship between bioaccumulation and the present state of metal enrichment and/or pollution.

2. Materials and methods

2.1. Sampling locations

Coral samples were collected from locations with various sources of contamination off the coastal of Taiwan (Fig. 2). Liang-Dong Bay, also known as Yin-Yang Sea (YYS), on the north eastern coast, is influenced by inputs from abandoned mines in the catchment. The water is considered polluted as a result of copper refining by the Taiwan Metal Mining Corporation with high concentration of iron, aluminum and other metals. Kueishan Islet (KI) is about 20 km away from the northeastern coast of Taiwan and is the location of white and yellow hydrothermal vents which emit fluids with high temperature, strongly acidic and metal enriched conditions. Green Island (GI) is about 33 km off the south eastern coast of Taiwan and located on the central path of Kuroshio Current which may influence the marine ecosystems of the area (Hwang et al., 2007; Tseng et al., 2013). In addition to coral sample collection, seawater temperature, salinity, pH and alkalinity were also measured according to the methods of Hung et al. (2008, 2013) and Peng et al. (2011).

2.2. Determination of dissolved heavy metals in seawater

Seawater samples were collected by SCUBA divers with clean polyethylene (PE) bottles (Fig. 2). All PE bottles were acid cleaned with nitric acid (analytical grade) for a period of 2 days and rinsed with distilled deionized water (DDW) thoroughly before use. When sampling, PE bottles were pre-rinsed further 3 times with *in situ* seawater before filling with seawater (Hung et al., 2009, 2012; Hung and Ho, 2013; Peng et al., 2011). The collected seawater samples were filtered through an online closed system in the clean room by acid-washed POLYCAP cartridges (Whatman, USA) with 0.2 μm pore size to remove particulate materials. The filtered seawater was preconcentrated with commercial chelating column specifically designed to concentrate cationic transition metals from high-ionic-strength matrices (Dionex MetPac CC-1, USA), which was a novel flow injection ion chromatograph (FI-IC) system. Metals in the preconcentrated seawater samples were determined by inductively coupled plasma mass spectrometer (ICPMS, Element XR, Thermo, USA). Detailed procedures can be found in Ho et al. (2010). Precision and accuracy were generally between 1% and 5% by using NASS-5 and CASS-4 (NRC, Canada) as reference seawater.

2.3. Determination of heavy metals in coral samples

Coral samples were collected by SCUBA divers from YYS at a depth of 13 m, near KI hydrothermal white vent at a depth of 21 m (about 30 m away from the main vent outlet), and GI at a depth of 15 m (Figs. 1 and 2). Six colonies of the *T. coccinea* were collected from each location. After collection, the *T. coccinea* samples were transferred to the laboratory and frozen at −20 °C until they were analyzed. Under the Olympus SZX10 microscope, soft tissues and skeletons from each coral sample were separated and extracted using high quality titanium forceps for subsequent trace metal analysis. Before digested, the skeleton was carefully washed using DDW to remove residual organic material, and then ultrasonically cleaned to remove any materials adhered to its surface. All skeleton samples were dried at 110 °C for 24 h, ground by using an agate mortar and pestle and then transferred quantitatively into a Teflon beaker, followed by adding 8 ml concentrated ultrapure HNO_3 for digestion for a period of 24 h. To minimize matrix effects, Yttrium (Y) (100 μg l^{-1}) was added to each standard and sample as the internal standard for final correction. Tissue sample of 0.1 g was transferred into the Milestone digestion vessel along with 10 ml of HNO_3, the vessels containing the samples were sealed and tightened prior to the digestion. The samples were placed in a microwave digestion system (Milestone, Model: START D) for digestion over 24 h.

After digestion, the sample was boiled at 95 °C until only about 1 ml of the digested solution was left (Shen and Boyle, 1988). The digested solution was diluted to a total volume of 8 ml with 2% HNO_3 for further determination. The internal standard Yttrium (Y) was added to minimize matrix effects for each standard and samples. Both skeleton and tissue solutions were analyzed with an inductively coupled plasma optical emission spectrometer (ICP-OES, Perkin Elmer Optima 2100DV equipped with an ultrasonic nebulizer) for Al, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Zn and Ca with detection limits (μg l^{-1}) as 6.73, 0.07, 0.05, 0.14, 0.89, 1.91, 0.1, 1.21, 1.62 and 3.64, respectively. The precision and accuracy of metal analyses were generally better than 8% evaluated by measuring a reference material (NRCC-DORM-2, dog fish muscle) from the National Research Council (NRC) of Canada. The bioconcentration factor (BCF) of heavy metal was calculated as the ratio between metal concentration in tissues (skeletons) and metal concentration in seawater (Ali et al., 2010; Mokhtar et al., 2012).

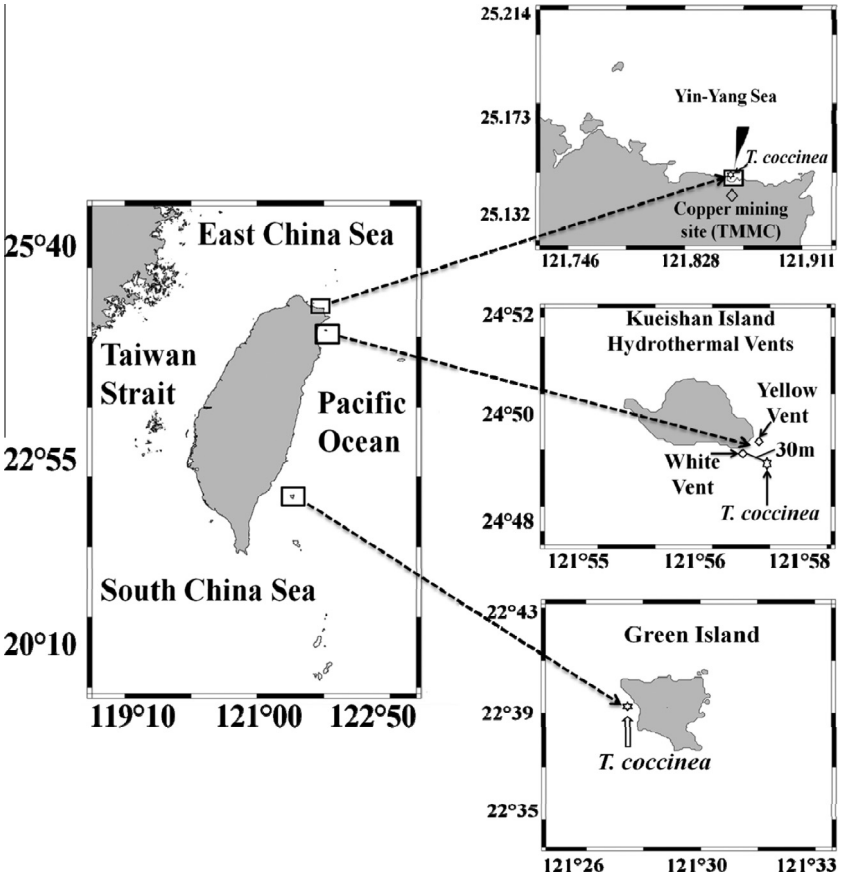

Fig. 2. Sample locations of Yin-Yang Sea (YYS), Kueishan Islet (KI), and Green Island (GI) around the eastern coast of Taiwan.

2.4. Statistical analyses

One-way ANOVA was used to compare statistically the metal concentrations in different skeleton and tissue samples from three sampling locations. Whenever significant differences were found among the skeleton and tissues samples, the pairs were compared further using Tukey's tests. Hence, the significance level was set at $p < 0.05$, according to procedures of Peng et al. (2011). The non-metric multidimensional scaling (NMDS) was applied to evaluate the relationships between metal concentrations in skeleton and tissue samples from different sampling locations. The Euclidean similarity (Martin, 1982) was applied to measure the distance among heavy metals before NMDS analysis. Statistical analyses were performed using the program STATISTICA 7.0, and the program Paleontological Statistics (PAST) computer software (Hammer et al., 2001) was applied to NMDS.

3. Results

3.1. Distributions of dissolved metals in sampling locations

Fig. 3 shows the distributions of dissolved metal concentrations and water parameters in the three locations. Relatively high metal concentrations occurred in seawater samples at YYS location. The concentrations were 5.09 ± 0.12 μM for Al, 0.31 ± 0.03 nM for Cd, 5.54 ± 0.64 nM for Co, 1.17 ± 0.19 nM for Cr, 113 ± 36 nM for Cu, 6.04 ± 2.07 nM for Fe, 176 ± 20 nM for Mn, 5.66 ± 0.27 nM for Ni, 0.19 ± 0.10 nM for Pb, and 20.7 ± 1.2 nM for Zn. The concentrations of dissolved metals at KI were generally lower than those found at YYS location except for Fe and Pb. Concentrations of dissolved Cd and Cr were within the same range at YYS and KI. In addition, the concentrations of the majority of dissolved metals were lower at GI than in YYS and KI, except for Co having a same range with KI and Al, Cu, Cr, Fe and Zn showing slightly higher concentrations in GI than in KI. The measured values of pH (8.09 ± 0.01), alkalinity (2.32 ± 0.02 mM), temperature (25.4 °C) and salinity (34.13) were recorded at YYS. The values of pH (7.30 ± 0.55), alkalinity (2.21 ± 0.03 mM), temperature (23.2 °C) and salinity (33.97 ± 0.51) were slightly lower at KI than those at YYS. The seawater conditions at GI generally displayed normal values for pH (8.38), alkalinity (2.29 ± 0.01 mM), temperature (26.2 °C) and salinity (34.52) (Fig. 3).

3.2. Accumulation of heavy metals in $CaCO_3$ skeletons of the T. coccinea

Fig. 4 shows the concentrations of various metals in *T. coccinea* skeletons. The highest and lowest concentrations of Al were identified in skeleton samples from KI and GI, respectively (Fig. 4a). The highest and lowest values of Cd were recorded in skeleton samples from GI and YYS, respectively (Fig. 4b). The samples from YYS and GI locations contained the highest and lowest values of Co concentration, respectively (Fig. 4c). Chromium concentration was highest in the KI samples and lowest in GI samples (Fig. 4d).

Copper was only detected in coral skeleton from YYS, and was generally below the detection limit in the GI and KI skeleton samples (Fig. 4e). The concentration of Fe in coral skeleton was highest in samples from YYS and lowest in those from GI (Fig. 4f). The concentration of Mn was highest in the YYS skeleton samples and lowest in those from GI (Fig. 4g). The highest and lowest concentrations of Nickel in coral skeleton were found at GI and KI, respectively (Fig. 4h). Compared with the KI samples, the

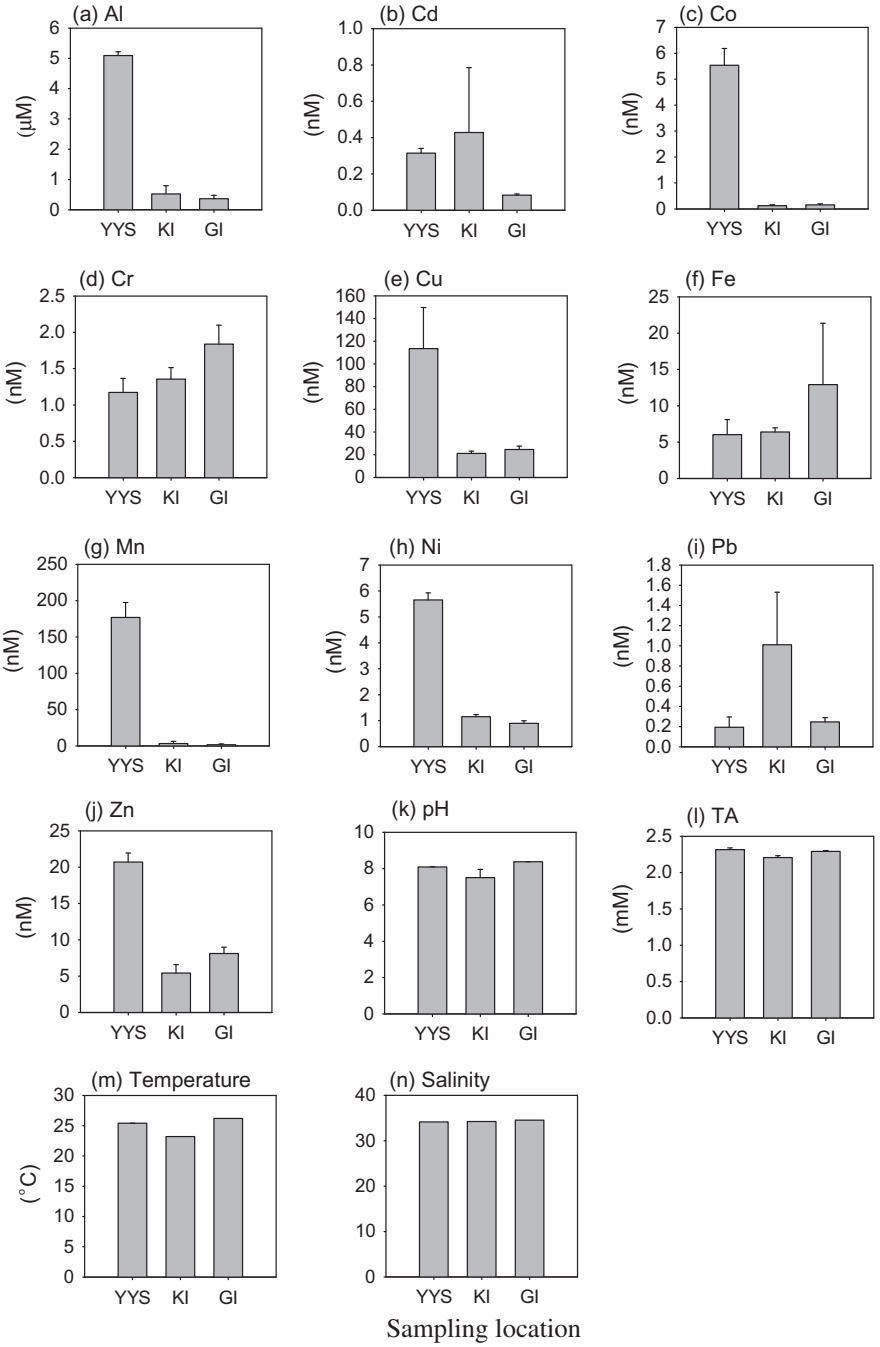

Fig. 3. Distributions of dissolved metals (a–j), pH (k), total alkalinity (TA) (l), temperature (m) and salinity (n) in seawater collected from YYS, KI and GI coral locations.

concentration of Pb was higher in the YYS and GI samples (Fig. 4i). However, the concentration of Zn was highest in skeleton samples from GI, followed by those from YYS and KI (Fig. 4j). The results demonstrated that the concentration was non-significant among the three locations ($p > 0.05$, one-way ANOVA) for Al, Cd, Cr, Cu, and Pb, although the results for Co, Fe, Mn, Ni and Zn were significant among the three locations ($p < 0.05$).

Fig. 5 shows the accumulation patterns of each heavy metal normalized with Ca in the skeleton samples. The results of the statistical analysis show no difference ($p > 0.05$) among three locations for Al/Ca, Cd/Ca, Cr/Ca, Cu/Ca, and Pb/Ca. However, compared with the skeleton samples from GI, those from YYS exhibited higher metal ratios for Co/Ca ($p = 0.006$, Fig. 5c) and Mn/Ca ($p = 0.02$, Fig. 5g). Similarly, the ratio of Fe/Ca was higher for samples from YYS than for those from both KI ($p = 0.016$) and GI ($p < 0.001$, Fig. 5g). Conversely, metal Ni/Ca was higher in the samples from GI than in those from both YYS ($p = 0.036$) and KI ($p = 0.025$, Fig. 5h). In addition, the Zn/Ca ratio was higher in the samples from GI than in those from both YYS ($p = 0.034$) and KI ($p = 0.011$, Fig. 5j).

3.3. Accumulation of heavy metals in tissues of the T. coccinea

Fig. 6 shows the concentrations of heavy metals in tissues of the *T. coccinea*. The highest concentration in YYS and lowest concentration in GI were found for Al, Cr, and Fe. The highest concentration in YYS and lowest concentration in KI were found for Co, Cu, Mn and Pb. However, Cd and Zn displayed highest and lowest concentrations in GI and YYS, respectively. In addition, Ni displayed highest and lowest concentrations in GI and KI, respectively.

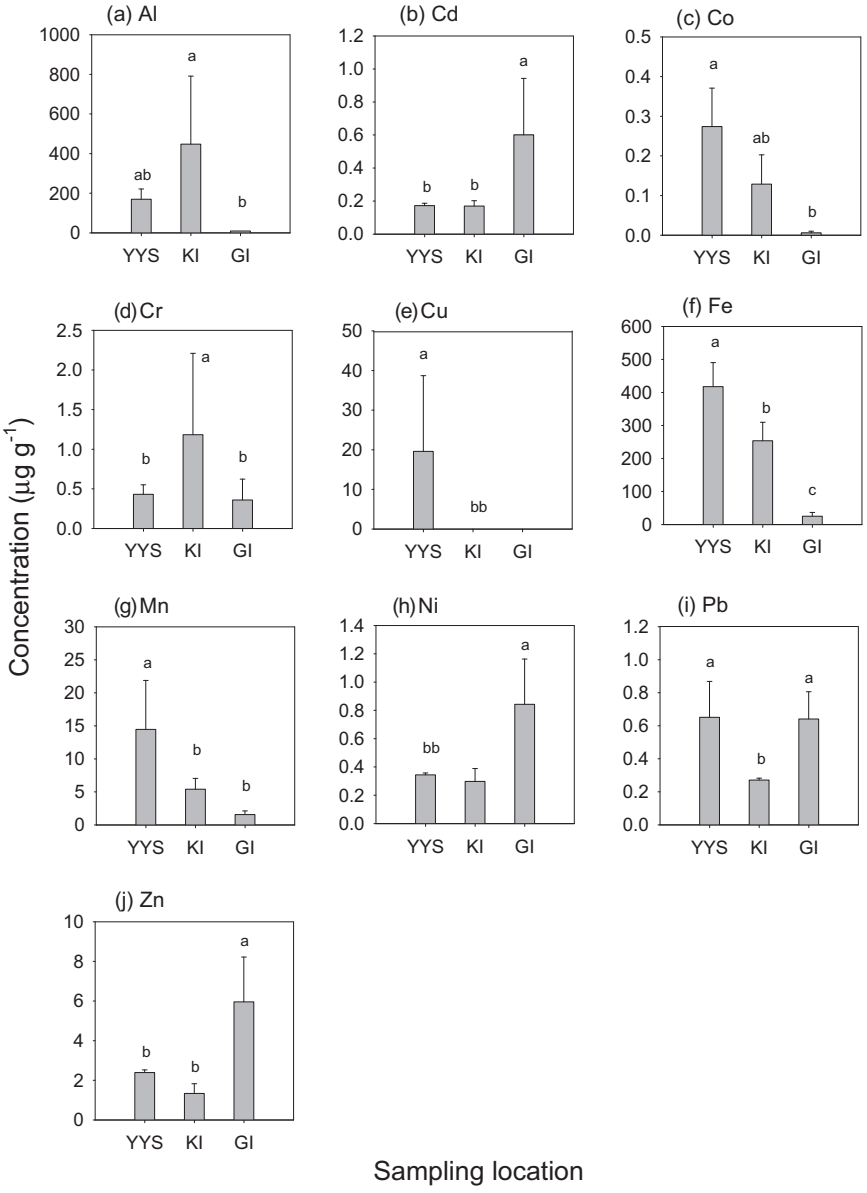

Fig. 4. Concentrations of heavy metals in $CaCO_3$ skeletons of the *T. coccinea* from the three study sites.

Among the three locations, the difference in metal concentrations in the tissue samples was non-significant for Al (Fig. 6a) and Cr (Fig. 6d) ($p > 0.05$, one-way ANOVA). However, compared with the samples from KI and GI, those from YYS exhibited a significantly greater concentration ($p < 0.01$) for Co (Fig. 6c), Cu (Fig. 6e), Fe (Fig. 6f), and Pb (Fig. 6i). Conversely, the concentration of Cd (Fig. 6b) was significantly higher in the samples from GI than in those from both YYS ($p = 0.005$) and KI ($p = 0.005$). The concentration for both Ni (Fig. 6h) and Zn (Fig. 6j) were significantly lower in the samples from YYS than in those from both KI and GI ($p < 0.05$). The concentration of Mn (Fig. 6g) was lower in the samples from KI than in those from both YYS ($p = 0.003$) and GI ($p = 0.013$).

3.4. Bioconcentration factors of heavy metals

Table 1 lists the distributions of BCF in the skeleton and tissue samples from the three locations. For the tissue and skeleton samples from GI, the BCF was substantially higher for all metals except Pb. No particular trend was observed for any metal among the three locations. For example, Cd exhibited the highest BCFs in the samples from GI, followed by those from YYS, and KI. However, Fe exhibited the highest BCFs in the samples from YYS, followed by those from KI and GI. The order of BCF magnitude was not always the same for all metals in either skeleton or tissue samples among the three locations. For the samples from YYS, the respectively highest and lowest BCF ranged from Co (861) to Fe (1,269,581) in the skeleton samples and from Co (2104) to Fe (6,141,481) in the tissue samples. For the samples from KI, the BCF ranged from Pb (1328) to Fe (778,197) in the skeleton samples and from Pb (2285) to Fe (4,336,771) in the tissue samples. In the samples from GI, the BCF ranged from Co (872) to Cd (65,885) in the skeleton samples and from Cu (9649) to Cd (1,330,224) in the tissue samples.

3.5. NMDS analysis of heavy metals in T. coccinea

The NMDS results show the accumulation patterns of heavy metals derived from skeleton (Fig. 7a) and tissue (Fig. 7b) samples collected from three locations. The patterns of metal accumulation in the skeleton samples from the various locations exhibited

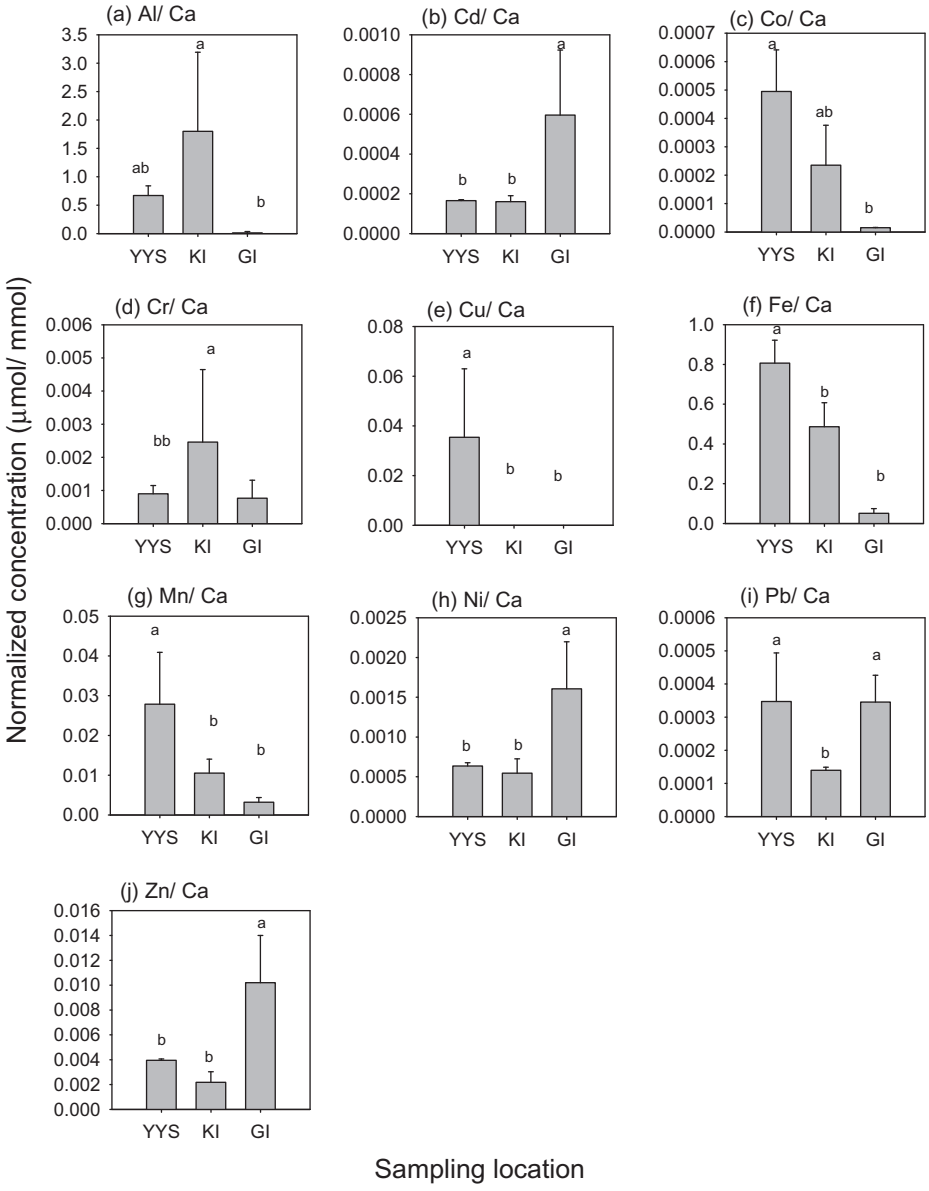

Fig. 5. Comparison of normalized conditions of metal/Ca in skeletons of the *T. coccinea* collected from YYS, KI and GI sites. The superscripts (a, b, c) denote significant differences ($p < 0.05$, one-way ANOVA) among three sampling locations, ND = not detected.

inconsistent features (Fig. 7a). The smallest variation in heavy metals was in the skeleton samples from GI. This indicates that the accumulation of the majority of heavy metals among the skeleton samples from GI were highly similar. The accumulation of Al and Fe exhibited a clear difference from the other metals among the skeleton samples collected from YYS and KI (Fig. 7a). Such patterns of metal accumulation in the skeleton samples indicate that the mechanisms releasing Fe and Al into seawater and accumulating in coral skeletons at both YYS and KI could be unique.

4. Discussion

4.1. Dissolved metals in ambient seawater

The effluent of abandoned mining sites previously operated by Taiwan Metal Mining Corporation contains high concentrations of heavy metals (Yang and Yeh, 1990; Chan et al., 2012). The effluent discharged into the YYS resulted in high concentrations of Al, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, and Zn in ambient seawater at the coral sampling location. However, these concentrations were lower than those found in the seawater near the effluent outlet (Chu et al., 1995) because of the mixing and dilution effects between effluent and seawater (Chan et al., 2012). Thus, the seawater at YYS exhibited the highest concentration for the majority of metals among the three locations. Previous research reported that the shallow water hydrothermal vents off the coast of KI comprise of white and yellow vents that emit acidic fluid containing high concentration of heavy metals (Chen et al., 2005); therefore, the concentrations of Al, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, and Zn were also high and secondary to those at YYS, despite the sample location being approximately 30 m away from the white vents. Compared with the metal concentrations in the seawater at YYS and KI, the detected levels at GI were relatively lower, indicating that GI is a remote island located on the Kuroshio path (Hwang et al., 2007; Tseng et al., 2013). Previous studies have expressed concern that metals can become toxic to certain marine organisms when the concentrations of specific bioactive metals elevate by only a few

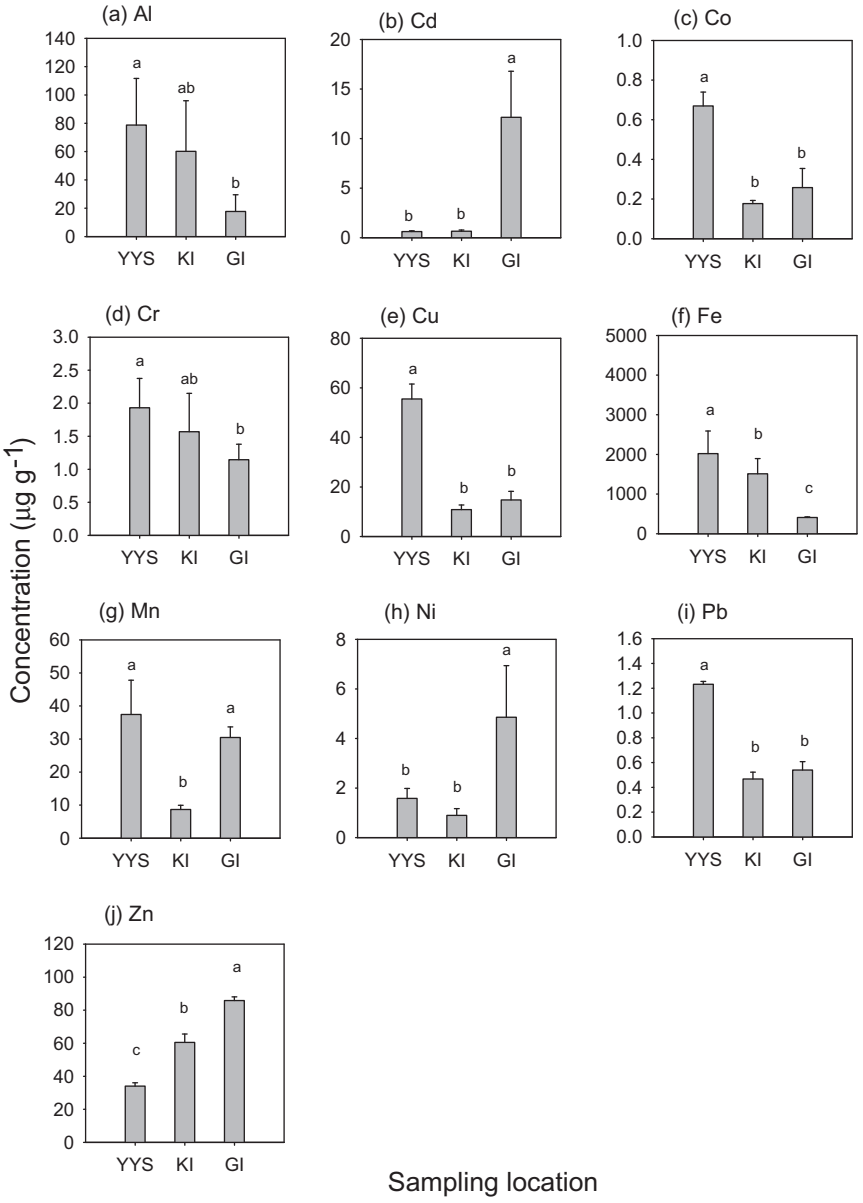

Fig. 6. Comparison of heavy metal concentrations in tissues of the *T. coccinea* collected from YYS, KI and GI sites. The superscripts (a, b, c) denote significant differences ($p < 0.05$, one-way ANOVA) among three sampling locations.

Table 1
The bioconcentration factors of heavy metals in the skeleton and tissue samples of the *T. coccinea* from YYS, KI and GI.

Location	YYS			KI			GI		
	Skeleton	Tissue	Tissue/skeleton	Skeleton	Tissue	Tissue/skeleton	Skeleton	Tissue	Tissue/skeleton
Al	1262	5872	4.65	32,478	43,597	1.34	960	18,536	19.31
Cd	4992	17,792	3.56	3610	13,870	3.84	65,885	1,330,224	20.19
Co	861	2104	2.44	18,049	24,786	1.37	872	28,416	32.59
Cr	7236	32,454	4.49	17,187	22,792	1.33	3849	12,284	3.19
Cu	3024	7891	2.61	ND	8250	–	ND	9649	–
Fe	1,269,581	6,141,481	4.84	728,197	4,336,771	5.96	36,048	580,011	16.09
Mn	1526	3949	2.59	30,420	48,938	1.61	18,779	364,423	19.41
Ni	1062	4891	4.61	4512	13,575	3.01	16,397	94,488	5.76
Pb	16,660	31,513	1.89	1328	2285	1.72	12,874	10,843	0.84
Zn	1808	25,785	14.26	3860	174,938	45.32	11,496	165,664	14.41

ND = Not Detected.

nanomoles (Chan et al., 2012). For example, phytoplankton and cyanobacteria are sensitive to changes in the concentrations of dissolved Cu and Cd (Sunda and Guillard, 1976; Payne and Price, 1999; Morel and Price, 2003). Therefore, the relatively high concentrations of dissolved metals in ambient seawater could have caused an increase in the bioaccumulation of metals in coral

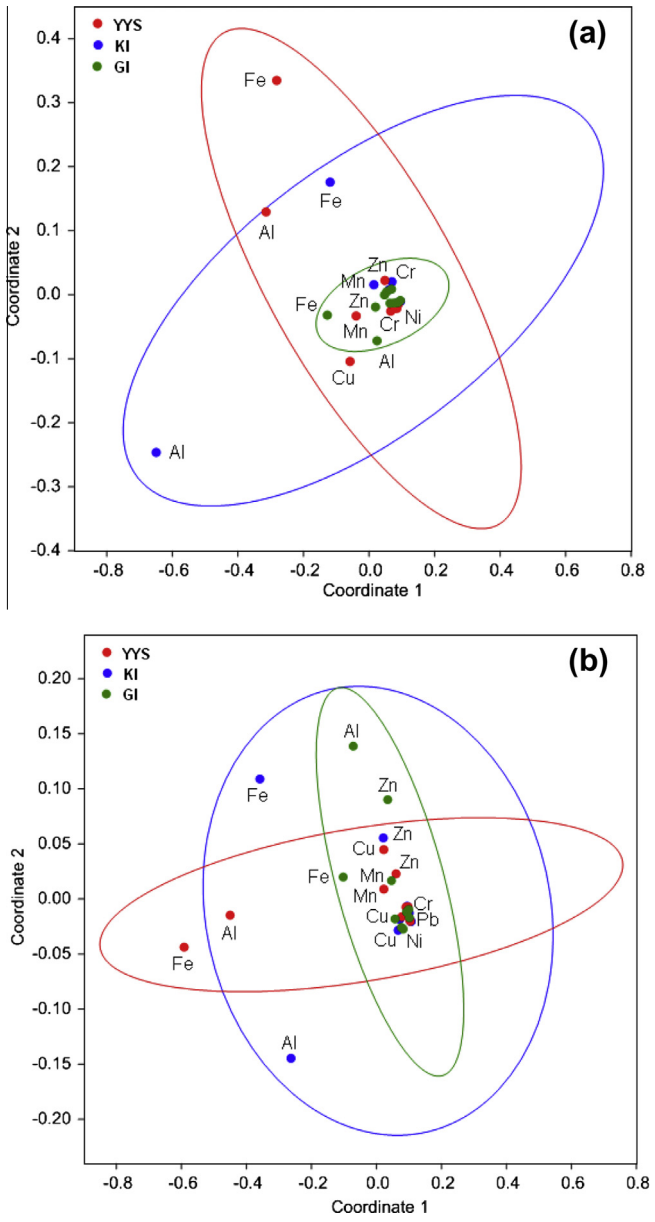

Fig. 7. Non-metric multidimensional scaling (NMDS) showing the relationship of all heavy metals in the skeleton (a) and tissue (b) samples of the *T. coccinea* collected from YYS, KI and GI. The circle is 95% confidence ellipses.

tissues and skeletons, thereby resulting in an unknown malfunction of the corals (Anu et al., 2007; Prouty et al., 2008).

4.2. Heavy metals in coral skeletons and tissues

The application of coral geochemical records of specific areas influenced by terrestrial inputs and anthropogenic pollution enables researchers to monitor the long-term effects of metal enrichments in seawater. Our analysis of metal accumulation in the examined *T. coccinea* skeleton and tissue samples could be indicative of the various degrees of metal pollution at YYS, KI, and GI locations. Meanwhile, the Ca-normalized metal concentrations (metal/Ca) in the skeleton samples were significantly different for Co/Ca, Fe/Ca, Mn/Ca, Ni/Ca and Zn/Ca, which corresponds with the condition of metal concentrations in the skeleton samples. This could indicate that external inputs caused the elevated metal concentrations in the skeleton samples, rather than the effects of coral aging and/or variations in the size of the skeleton bodies.

Several previous studies have reported the accumulation of metals in skeletons and tissues in numerous marine environments (Scott, 1990; Reichelt-Brushett and McOrist, 2003; Al-Rousan et al., 2007; Prouty et al., 2008). Conversely, previous research showed that certain coral species did not accumulate metals (Brown and Holley, 1982). Esslemont et al. (2000) reported that metal concentrations in tissues might be determined by differential selectivity of corals for metals. Thus, relatively high concentrations of certain metals in specific organisms could be relevant to their utilization of that metal (Alcorlo et al., 2006). For example, Zn is utilized as an active center for metaloenzymes and activators of other enzymes, and it is usually abundant in digesting organs. Previous studies have shown that Cu has an integrated role in the respiratory pigment; therefore, Cu and Fe are abundant in various marine organisms (Alcorlo et al., 2006; Peng et al., 2011). Coral tissues and skeletons can capture metals through various mechanisms other than through the exposed surface area. The ability of coral skeletons to incorporate metal as a part of their structure is a critical factor; however, not all metals are suitable for uptake by corals for transfer to their skeletons (Reichelt-Brushett and McOrist, 2003). It is widely recognized among scholars that the bioaccumulation mechanism of metals in coral skeletons depends on the biomineralization process during skeleton formation (Dar, 2004; Dar and Mohammed, 2006).

In this study, high concentrations of heavy metals in the *T. coccinea* could be primarily attributable to the differential ability of metal incorporation into the skeletons and tissues of the examined corals, because we observed a significant difference in metal accumulation between the skeleton and tissue samples of the *T. coccinea*. The metal accumulation was also substantially higher in the tissues (living component) than in the skeletons (non-living component). The ratio between the tissue and skeleton concentrations ranged from 0.84 for Pb in the samples from GI to 45.3 for Zn in the samples from KI, and >70% of all ratios are >2.0. Therefore, the tissue appeared to accumulate a higher concentration of metals. Previous studies (Table 2) have shown that the massive brain coral *Diploria strigosa* (hard corals) and *Montipora digitata* (soft corals) appear to have the ability to bioaccumulate substantially more metals than other species. This is also supported by the findings of close relation between metal accumulation and coral morphology (Anu et al., 2007). Similarly, the corals used in this study also accumulated a relatively high concentration of metals from YYS and KI with high metal loads; our results are in agreement with the findings of previous studies (Haynes and Johnson, 2000; Mohammed and Dar, 2010) which showed that metal concentrations of Cd, Cu, Pb, Ni, and Zn are highly associated with biological assimilation of elevated metals from hazardous environments such as landfills or mining sites. In addition, the environmental condition of GI was considered a relatively unpolluted ecosystem; thus, relatively low concentrations of heavy metals were detected in the seawater, skeletons, and tissues of the *T. coccinea*. Thus, high concentrations of metals in skeletons and tissues of *T. coccinea* are the result of anthropogenic and natural inputs in the studied areas.

According to NMDS, the common patterns of metals in the skeleton (Fig. 7a) and tissue (Fig. 7b) samples can be summarized as follows: (a) Metals Al and Fe have a similar pattern in specimens of skeleton and tissue from YYS and KI, showing locations significantly different from other metals. The difference was caused from a higher concentration of both metals. Both metals also exhibited high levels of accumulation in the samples from YYS and KI (Figs. 4–6); (b) The distribution pattern of heavy metals in the skeleton and tissue samples is closer in the samples from GI than in the samples from YYS and KI. This pattern is in accord with the fact that metal accumulation in skeleton and tissue samples was lower in GI than in YYS and KI.

Table 2
Comparison of mean metal concentrations in coral skeletons and tissues of different coral species collected from different geographical regions.

Skeleton				Tissue			
Species name	Habitat	Metal concentration ($\mu g\ g^{-1}$)	Reference	Species name	Habitat	Metal concentration ($\mu g\ g^{-1}$)	Reference
Acropora tenuis	Magnetic Island	Cd (0.001), Cu (0.06), Fe (16.3), Pb (0.04), Zn (1.8), Mn (0.15), Ni (1.1)	Reichelt-Brushett and McOrist (2003)	*Acropora tenuis*	Magnetic Island	Cd (0.045), Cu (1.0), Fe (23.3), Pb (0.36), Zn (19.5), Mn (1.38), Ni (1.8)	Reichelt-Brushett and McOrist (2003)
Acropora nobilis	Darwin Harbor, Heron Island of Australia	Cd (0.01), Cu (0.32), Fe (NA), Mn (NA), Pb (0.09), Zn (0.86)	Esslemont (1999)	*Montipora digitata*	Lakshadweep Archipelago	Cu (0.49), Cr (0.92), Co (0.23), Ni (0.50), Pb (0.31), Zn (0.68), Mn (0.72), Cd (0.22), Fe (16.55)	Anu et al. (2007)
Porites astreoides	North-west coast of Venezuela	Cd (NA), Cu (16.33), Fe (62.05), Mn (NA), Pb (0.208), Zn (10.67)	Bastidas and Garica (1999)	*Actinodiscus*	Wadi El-Gemal	Fe (0.09), Mn (0.006), Ni (0.01), Cu (0.009), Zn (0.05), Pb (0.004)	Mohammed and Dar (2010)
Acropora formosa	Nelly Bay, Australia	Cd (0.19), Cu (7.2), Fe (NA), Pb (0.24), Zn (37)	Esslemont et al. (2000)	*Porites compressa*	Hurghada	Fe (0.04), Mn (0.01), Ni (0.015), Cu (0.014), Zn (0.17), Pb (0.011)	Mohammed and Dar,(2010)
Acropora valida	Taba, Gulf of Aqaba	Cd (1.43), Cu (9.35), Fe (291), Mn (NA), Pb (1.67), Zn (8.63)	Khaled et al. (2003)	*Alcyonium dendroides*	Wadi El-Gemal	Fe (4.05), Mn (0.01), Ni (0.016), Cu (0.01), Zn (0.03), Pb (0.015)	Mohammed and Dar (2010)
Porites astreoides	Jordanian Gulf of Aqaba	Cu (NA), Fe (25.76), Mn (8.22), Pb (47.91), Zn (5.52)	Al-Rousan et al. (2007)	*Subergorgia suberosa*	YYS	Cu (5.64), Zn (38.76), Cd (63.43)	Chan et al. (2012)
Stylophora pistillata	Red Sea coast Egypt	Cu (2.3), Fe (71.1), Mn (10), Pb (24.7), Zn (30.2)	Abdelbaset et al. (2012)	*Fungia fungites*	Red Sea	Zn (5.9), Pb (6.7), Mn (1.9), Fe (17.8), Cr (1.6), Co (12.8), Ni (21.7), Cu (1.3)	Abdelbaset et al. (2012)
Tubastraea coccinea	YYS	Al (169.3), Cd (0.2), Co (0.3), Cr (0.4), Cu (21.3), Fe (417.6), Mn (14.5), Ni (0.3), Pb (0.7), Zn (2.4)	This study	*Tubastraea coccinea*	YYS	Al (0.8), Cd (0.6), Co (0.7), Cr (1.9), Cu (55.5), Fe (2.0), Mn (37.4), Ni (1.6), Pb (1.2), Zn (34.1)	This study
Tubastraea coccinea	KI	Al (44.8), Cd (0.2), Co (0.01), Cr (1.2), Cu (ND), Fe (253.9), Mn (5.4), Ni (0.3), Pb (0.3), Zn (1.3)	This study	*Tubastraea coccinea*	KI	Al (0.6), Cd (0.7), Co (0.2), Cr (1.6), Cu (10.8), Fe (1.5), Mn (8.7), Ni (0.9), Pb (0.5), Zn (60.5)	This study
Tubastraea coccinea	GI	Al (9.2), Cd (0.6), Co (0.007), Cr (0.4), Cu (ND), Fe (25.4), Mn (1.6), Ni (0.8), Pb (0.6), Zn (6.0)	This study	*Tubastraea coccinea*	GI	Al (0.2), Cd (12.1), Co (0.3), Cr (1.1), Cu (14.7), Fe (0.4), Mn (30.5), Ni (4.9), Pb (0.5), Zn (85.5)	This study

NA = Not Available.

4.3. Bioconcentration factors of metals in corals

The BCF is substantially higher in the tissue samples than in the skeleton samples, except for the concentration of Pb in the samples from GI (Table 1). Metal tends to accumulate in the living component (i.e., the tissue) rather than in the non-living component (i.e., the skeleton), especially for biologically essential metals such as Co, Fe, Ni, and Zn. Although Cd is not an essential element, it is a nutrient-type metal in oceans. Different BCFs identified among the three locations for the same metal could indicate different uptake processes when external metal inputs vary (Dar, 2004; Dar and Mohammed, 2006). Moreover, the sequence of magnitude among these metals differs between the BCF and dissolved concentration for a location. This could imply that corals also uptake metals from food webs other than directly from seawater. The availability of zooplanktons could be the most probably food source for corals. Numerous previous studies have shown that metal accumulation can also occur through food (zooplankton) and water intake, with any differences being dependent on the species, metals, and food sources (Weeks and Rainbow, 1993; Munger and Hare, 1997; Anthony, 2000). Further studies might need to quantify the bioaccumulation rates of metals transferred from copepods to corals through the complex marine food web.

5. Conclusion

Several lines of evidence have shown differential metal bioaccumulation in coral skeletons and tissues from seawater in YYS, KI, and GI under various pollution conditions. Relatively high metal accumulation in the skeleton and tissue samples from YYS and KI are associated with high metal concentrations in seawater derived from high metal loads. Metal accumulation is substantially higher in the tissues than in the skeletons, which is supported by the substantially higher BCF in tissues than in skeletons. Each metal yields different accumulated ranges between skeletons and tissues, providing a strong indication that such coral has distinct selectivity for assimilating metals from seawater. This study supports the hypothesis that metal accumulation in skeletons and tissues is suitable for monitoring the long-term effect of coral in various polluted environments. However, tissues are more sensitive monitoring tools than skeletons are. Further study may be necessary to elucidate the mechanism of metal accumulation in coral skeletons and tissues.

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