Tridacna: Sentinels of Heavy Metal Pollution in Torres Strait Waters - a Critical Evaluation

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Abstract

There is an urgent need to evaluate the impact of Papua New Guinea's gold and copper mining activities on the biotic components of the Torres Strait. Increased metal mobilization within this region will undoubtedly result in the increased accumulation of metals in certain species. Although the ecological implications of this are uncertain at the present time, metal enrichment of vital subsistence, commercial and recreational species could prove significant from a public health viewpoint and have devastating economic repercussions for the peoples of the region. The regular monitoring of metal levels available to the biota within this area is, therefore, of critical importance if such consequences are to be avoided. Surveillance studies of this nature should include those species whose elemental concentrations reflect changes in the ambient metal availability of their immediate surroundings. While such bio-monitor organisms for tropical regions of the world have received less attention than their temperate water counterparts, some candidate species have been suggested. Among these, the tridacnid clams, Tridacna maxima and T. crocea rank very highly and fulfil several of the necessary bio-monitor prerequisites. As a consequence, studies were undertaken with the latter species to identify uptake and depuration kinetics of copper, zinc, cadmium, lead and mercury. The objectives of these investigations were to fine-tune the clam's role as a monitoring tool with respect to sampling frequency and interpretive capacity. The findings of the study are evaluated here along with some inherent weaknesses and limitations of their use.

Introduction

Trace metals are a normal component of the world around us and at least 12 are known to be essential for life (George 1990). The natural processes primarily responsible for their mobilization in the environment include volcanic eruptions and the physical and chemical weathering of rocks (Turekian 1971). Principal anthropogenic processes responsible for their mobilization include mining, smelting and refining, which collectively outweigh contributions achieved by natural forces (Brian 1976).

Although not all mined metals pose an immediate threat to the aquatic environment, those of greatest concern (based on toxicity, background concentrations and industrial needs) are copper, lead, cadmium, zinc and mercury (Phillips 1980). These metals are being mined and mobilized, on a world wide basis, at rates which exceed simple geological processes of weathering by factors of 32, 29, 16, 15 and 4 respectively (Bryan 1976). They are also the same metals currently impacting upon the marine resource of the Gulf of Papua and adjacent waters of the Torres Strait as a result of mining activities in Papua New Guinea.

The two major areas of concern associated with elevated inputs of trace metals into aquatic environments, like the Torres Strait, are direct toxicity to sensitive species and excessive metal accumulation by species harvested for human consumption. Impacted areas should therefore be continually monitored if spatial and temporal trends in metal abundance and bioavailability are to be adequately identified.

Such monitoring strategies may involve the analysis of water, sediments and biota. Each of these components presents certain problems either from a sampling, analytical or interpretive standpoint (Phillips 1977, 1980, 1990). In general, however, the analysis of biota is by far the most preferred single method of approach being generally simpler, quicker and cheaper than the other two. It also provides a measure of a metal pollutant's bioavailability, a feature which is not readily identified by water or sediment analysis alone.

Although considerable emphasis has been placed on the development and refinement of bio-monitoring programs for temperate waters, little comparable data exists for tropical reef waters. Problems associated with the selection of bio-monitors from tropical regions include the generally low abundance and often patchy distribution of promising species, whose biology is often poorly known and whose reliability as an indicator organism remains to be established.

Recognizing these constraints Burdon-Jones and Denton (1984 a and b) attempted to evaluate the monitoring potential of over 120 marine species from the Great Barrier Reef (Denton and Burdon-Jones 1986a, b, c). Based on abundance, metal accumulation capacity, and apparent indicator ability, six organisms ultimately emerged as potentially useful indicator species. They included one species of green algae (*Chlorodesmis fastigiata*), a fish (*Lutjanus carponotatus*) and four species of bivalve mollusc, (the chamid, *Chama iostoma*; the mytilid, *Septifer bilocularis*; and the tridacnid clams *Tridacna crocea* and *T. maxima*). Of these, the tridacnid clams clearly stood out as the most promising candidates for future monitoring work in this region and adjacent waters of Torres Strait (Denton 1986) on the basis that:

- One or both species were found at all sites visited in numbers sufficient to sustain an ongoing monitoring programme.
- They were readily identifiable, easy to collect and provided ample tissue for analysis.
- They showed an extraordinary capacity to accumulate a wide range of metals and reflect areas of metal enrichment.
- Being sedentary, metals accumulated by them reflected available levels in their immediate surroundings.
- They were geographically widespread and could, therefore, be incorporated into pollution monitoring networks elsewhere in the Indo-Pacific region.
- As phototrophs they were especially well suited to monitoring trace metals in the clear, relatively barren waters of the Great Barrier Reef where other bivalve bio-monitors may fail to survive.
- Current interest in the culture of clams for food and restocking reefs has greatly increased our understanding of their biology and facilitated their availability as transplant organisms for bio-monitoring purposes.

Although the above work clearly identified tridacnid clams as extremely valuable indicators of trace metal pollution, additional research was necessary to determine metal turnover times and the precise relationship between levels accumulated and those in the overlying water column. Such information was considered essential for quantitative interpretation purposes. In addition, the prescription of a sampling frequency necessary to provide a reasonably continuous record of a metal's time-averaged bioavailability could not proceed without it.

Subsequent metal kinetic studies were therefore conducted with *T. crocea* and the findings and implications of these results from a monitoring viewpoint, together with relevant earlier work, are reviewed here.

Trace Element Dynamics in Tridacnid Clams

Accumulation Capacity

Most of the limited information on the trace metal accumulation capacity of tridacnid clams reflects the endeavours of the Soviet scientists, Khristoforova and co-workers (Khristoforova 1980, Khristoforova *et al.*1979, 1983).

In Australia, attention first focused on this group in 1974 following the discovery of unusually high nickel concentrations in the tissues of *T. maxima* from Orpheus Island, north of Townsville (Burdon-Jones *et al.*,1975). The possible connection between these findings and the close proximity of a recently established nickel refinery stimulated an interest in the group as potentially useful bio-monitors of nickel pollution. However, the connection proved to be unfounded as clams taken well away from the area in later studies also demonstrated a similarly high accumulation capacity for this

element. Nevertheless, the monitoring potential for several other metals was indicated and gave impetus to further investigations in which clams were analyzed from a number of other locations along the entire length of the Great Barrier Reef between 1976 and 1983 (see Table 1).

Table 1: *Tridacna* Sampling Locations Along the Great Barrier Reef

Far Northern Section:	***Northern Section:***
York Island (19/11/78) [1,2]	Carter Reef (12/2/81) [1,2]
Murray Island (18/11/78) [1]	Lizard Island (Feb 81-Jan 83) [1,2]
Great Detached Reef (14/11/78) [1]	Linnet Reef (11/2/81) [1,2]
Corbett Reef (12/11/78) [1,2]	Low Island (10/11/78) [2]
Haughton Island (11/11/78) [2]	
Central Section:	***Southern Section:***
Orpheus Island (Dec 80-Jan 83) [1,2]	Heron Island (14/1/81) [1]
Myrmidon Reef (27/8/81) [1]	Wistari Reef (12/1/81) [1]
Flinders Reefs (29/8/81) [1]	Sykes Reef (13/1/81) [1]
Havannah Island (5/12/76) [1]	
Kelso Reef (5/12/76) [1]	
Herald Island (22/2/76) [2]	
Acheron Island (18/3/77) [1,2]	
Wheeler Reef (2/9/78) [1]	
Davies Reef (23/11/76) [1]	
Broadhurst Reef (23/11/76) [1]	
Bowden Reef (4/12/75) [1]	
Magnetic Island (30/10/83) [1,2]	

Superscript [1] and [2] denote the collection of *Tridacna maxima* and *T. crocea* respectively.

Table 2 summarizes the data for levels of copper, zinc, cadmium, lead and mercury in *T. maxima* tissues from four locations in the central region of the Great Barrier Reef. The chosen metals have high pollution potential in the Torres Strait region and, were therefore considered to be of greatest importance here. The four locations were selected on the basis that the corresponding data encompasses 95% of data obtained from all other locations. Thus, the values for Myrmidon and Flinders Reefs are typical for pristine environments, well away from coastal and anthropogenic influences, whereas those for Orpheus and Magnetic Islands reflect nearshore environments exposed to mild and moderate degrees of trace metal impaction respectively.

Of the tissues examined, the kidney clearly demonstrates the highest accumulation capacity and greatest inter-location variability for the elements listed. It is noteworthy that this organ also accumulates high concentrations of several other metals as summarized in Figure 1.

The ability of the kidney to concentrate a diversity of metals infers an abundance of non-specific metal binding sites in this tissue which immobilize and retain metals for relatively long periods of time. Of central importance here are the numerous laminate concretions (nephroliths) which lie in the large central vacuole of the ciliated columnar cells (nephrocytes) lining the renal tubules. These granular bodies are

Table 3. Trace Element Levels in Kidney Tissue of the Clams, *Tridacna maxima* and *T. crocea* from Torres Strait (data are range and (geometric mean)).

Species	Location	Sampling Date	N	Metal Concentrations ug g-1 Dry Weight				
				Copper	Zinc	Cadmium	Nickel	Lead
T. maxima	Murray Island	18/11/78	2	2.3-4.1 (3.1)	1.1-4.1 (2.2)	1.0-2.1 (1.5)	1536-2569 (1986)	6.4-9.4 (7.8)
	York Island	19/11/78	2	2.4-2.6 (2.5)	65.2-94.4 (78.5)	59.0-85.2 (70.9)	474-1313 (789)	8.7-25.4 (14.9)
T. crocea	York Island	19/11/78	4	3.8-4.9 (4.5)	6.2-8.8 (7.7)	2.9-27.5 (12.6)	1762-4284 (3018)	27.8-34.6 (31.1)
	York Island[a]	15/8/85	7	1.7-4.6 (3.0)	242-1389 (727)	44.5-243 (111)	547-1566 (1023)	28.2-37.3 (29.9)
	Marakai Island	15/8/85	8	2.7-19.0 (4.6)	1.8-98.1 (5.9)	70.3-252 (140)	911-2922 (1414)	22.2-60.3 (47.7)
	Zagai Island	28/6/85	4	4.1-6.0 (4.3)	4.3-114 (14.3)	75.7-173 (119)	256-1324 (801)	21.5-35.2 (28.4)

[a] York Island clams were collected close to a popular mooring site for large fishing vessels and other water craft. Clams from all other locations were collected well away from any known localized sources of trace metal pollution.

250 km the nearest major city of Cairns. For all intents and purposes, the island and its surrounding waters are regarded by many as pristine. However, renal zinc concentration in both *T. crocea* and *T. maxima* from the landward side of the island indicated a very definite point source of zinc contamination in the Anchor Bay/ Watson's Bay area (Figure 2a). A similar profile though considerably less pronounced was also apparent for cadmium (Figure 2b), a chemically similar metal, known to coexist with zinc in nature and in metallurgical products.

At first, the source of contamination was not readily identifiable; a problem which was compounded by the lack of tell-tale evidence of zinc and cadmium enrichment in water samples collected simultaneously from each site. However, it was later learned that from mid October to January, every year, both bays are heavily congested with fishing boats and various support vessels in pursuit of black marlin (*Makaira indica*) and other large game fish in the area. Zinc and, to a lesser extent, cadmium contributions from anti-fouling and anti-corrosive marine paints, sacrificial anodes, galvanized structures, brass fittings, mooring gear etc., therefore, seemed to be the logical explanation for the profiles depicted by the clams.

Assuming this hypotheses to be correct, the lack of supporting evidence for metal enrichment in surface waters from Watson's Bay and Anchor Bay may be explained by the fact that both clam and water samples were collected just prior to the opening

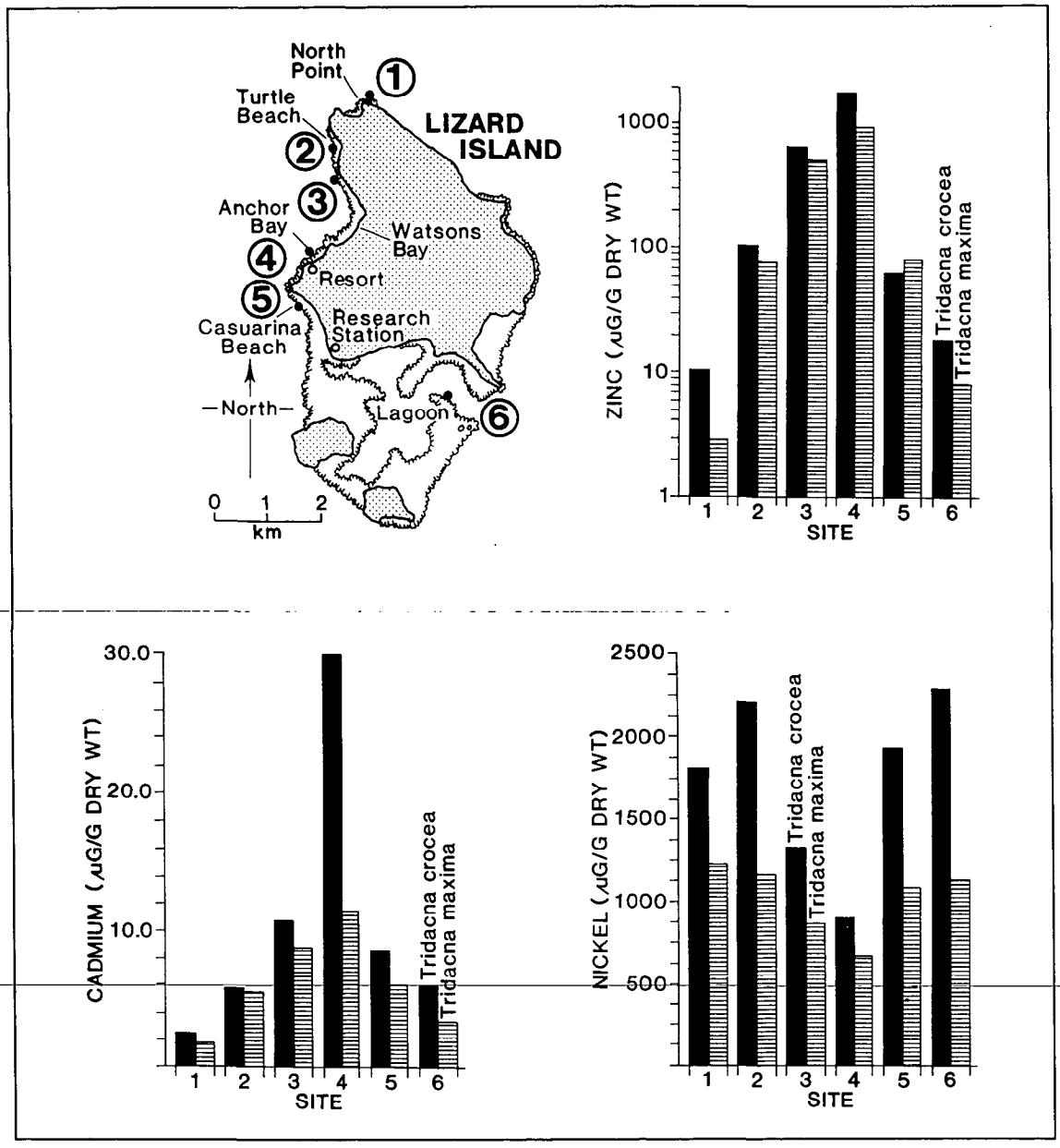

Figure 2. Zinc, cadmium and nickel profiles depicted by the kidney of *Tridacna maxima* and *T. crocea* from Lizard Island (Oct. 1982) on the Great Barrier Reef. (values are geometric means; n = 5).

of the 1982 marlin fishing season. Hence, elevated zinc and cadmium levels in the water column from the previous year had long since been flushed from the bays during the intervening period of relatively low boating activity. The fact that both metals were retained by the clam kidney long after ambient levels had returned to normal, highlights the importance of these bivalves in providing the investigator with information which might otherwise be lost by the analysis of water alone.

The renal nickel profiles determined in clams from Lizard Island (Figure 2c) deserve comment here insofar as they appear inversely related to those for zinc and cadmium. Nickel is naturally concentrated by the tridacnid kidney and levels found in clams from sites 1, 2, 5 and 6 at Lizard Island are typical of clean, outer barrier sites, (see Burdon-Jones and Denton 1984 a). Quite possibly, the diminished levels found in clams from the Watson's Bay/Anchor Bay region (sites 3 and 4) reflect displacement of nickel from renal binding sites by zinc. In any event, the utility of tridacnid clams for monitoring changes in ambient nickel availability is questionable and requires further evaluation.

Uptake and Depuration Kinetics

Although greatly encouraged by the Lizard Island study, several important questions emerged from this work regarding metal turnover times, and the precise relationship between levels accumulated by the clam kidney and those in the surrounding water. Answers to these were essential in order to fine tune the organism's use as a monitoring tool.

Subsequent kinetic studies with *T. crocea*, indeed, revealed that time related changes in renal concentration factors, for mercury, cadmium and lead, were independant of the concentration changes in the surrounding water (Figure 3). Expressed another way, renal accumulation rates, for all three metals, were directly proportional to their ambient concentrations. Such a relationship indicated little to no metabolic regulation of these elements and fulfilled one of the basic requirements of a bio-monitor (Haug *et al.* 1974).

Loss rates for all three metals were approximately linear with time, when plotted on semi-log graph paper, implying that the kidney acts as a single compartment and obeys first-order kinetics (Klaassen *et al.* 1986). This is the simplest of kinetic models describing residue dynamics and requires that uptake and depuration rates are directly proportional to levels in water and tissues respectively. As both requirements appeared to have been satisfied by the clam kidney, the uptake and depuration curves were, fitted to the respective data sets (Figure 4) following the estimation of the appropriate rate constants (k_u and k_d) as described by Spacie and Hamelink (1985).

The continued accumulation of all three metals (cadmium in particular) by the kidney during the first few weeks of the depuration reflects amounts offloaded from the other tissues.

Often, organisms behave quite differently in the field compared with the laboratory. However, the first-order kinetics model adequately described copper, zinc and lead uptake and depuration in *T. crocea* translocated and relocated between relatively clean (Orpheus Island) and polluted (Townsville Harbour) environments at different

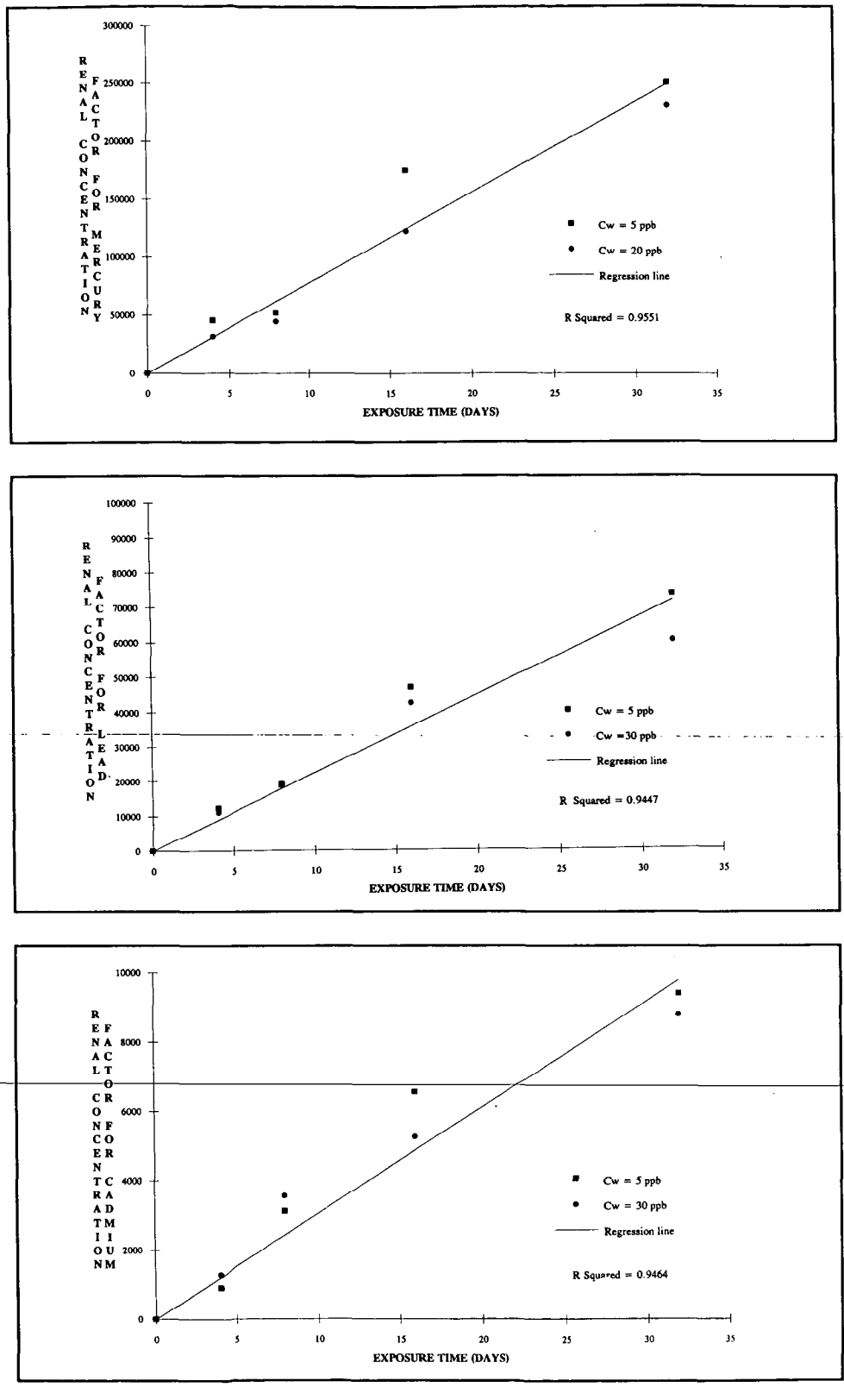

Figure 3. *Tridacna crocea* renal concentration factors for mercury, lead and cadmium as a function of time. (Each plot represents the geometric mean; n = 10. Cw = test concentration ($\mu g l^{-1}$) of metal in seawater).

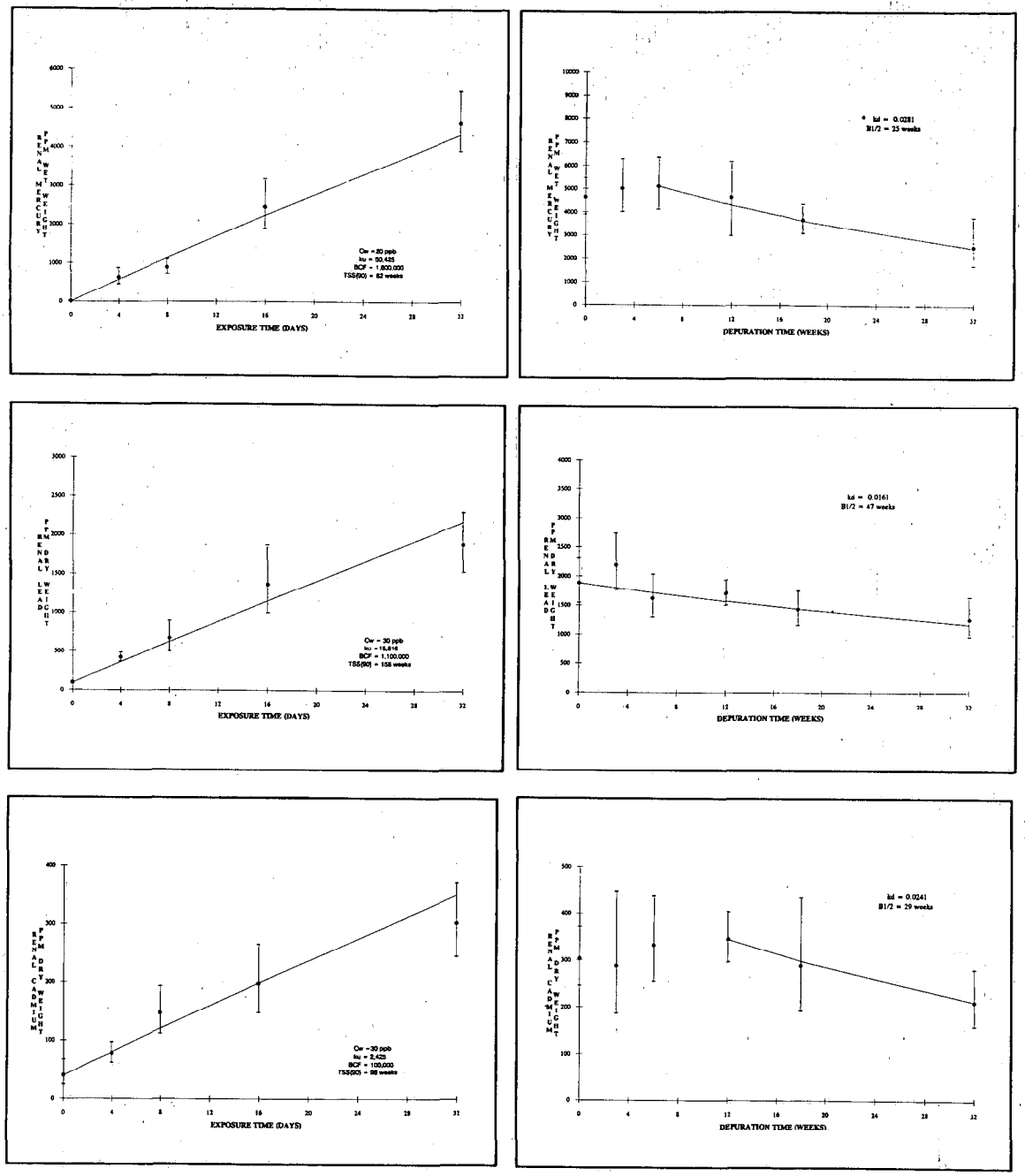

Figure 4. Uptake and depuration of mercury, lead and cadmium by the kidney of *Tridacna crocea*. (Each plot represents the geometric mean of 95% confidence interval; n = 10. Cw = test concentration ($\mu g l^{-1}$) of metal in seawater; ku = uptake rate constant (wks^{-1}); BCF = biological concentration factor at steady state; TSS(90) = time to reach 90% of steady state concentration; kd = depuration rate constant (wks^{-1}); B1/2 = biological half-life).

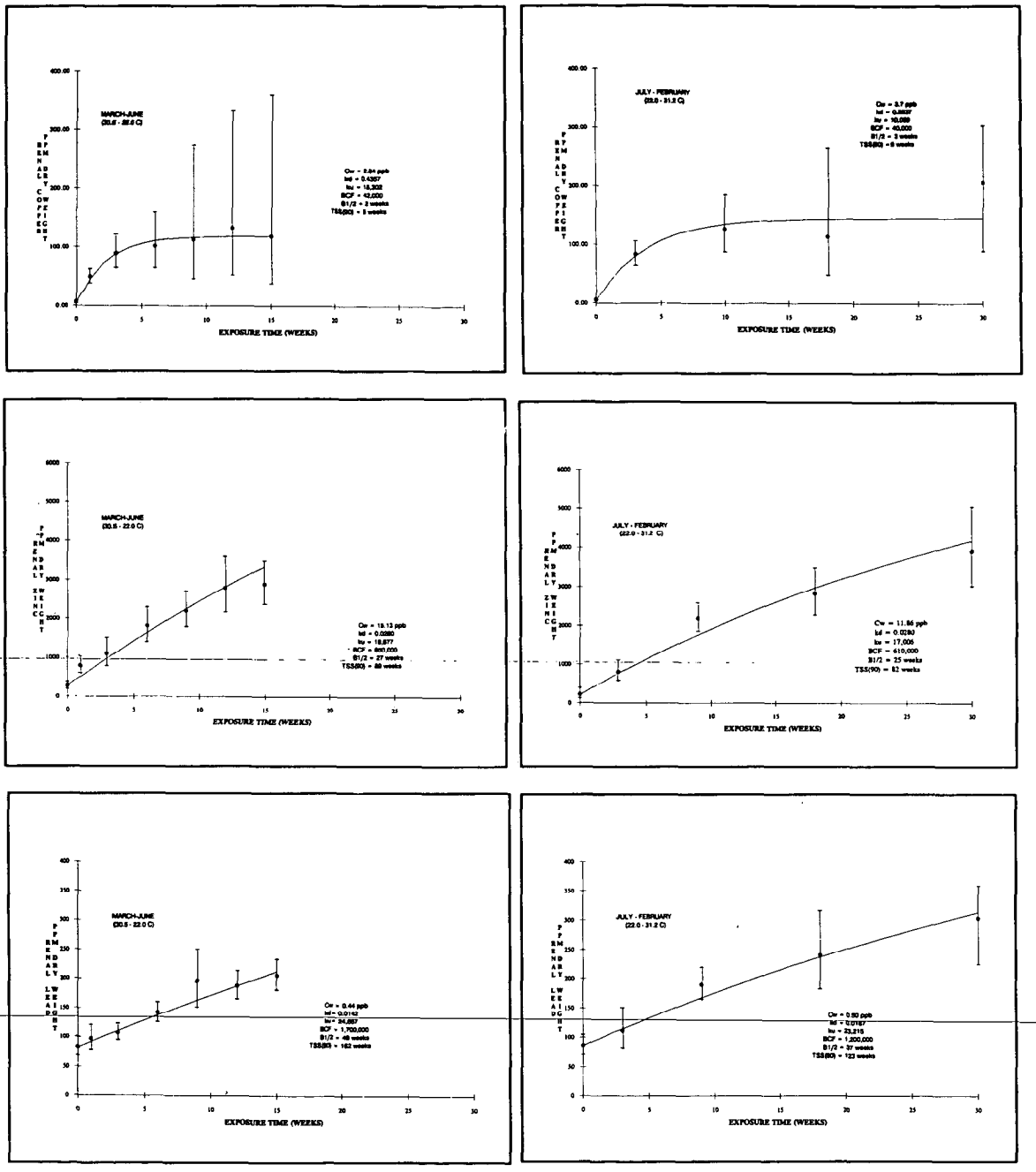

Figure 5. Uptake of copper, zinc and lead by the kidney of *Tridacna crocea* held in Townsville Harbour at different times of the year. (Each plot represents the geometric mean and 95% confidence interval; n = 10. Cw = test concentration of metal in seawater ($\mu g l^{-1}$); ku = uptake rate constant (wks^{-1}); kd = depuration rate constant (wks^{-1}); BCF = biological concentration factor at steady state; B1/2 = biological half-life; TSS(90) = time to reach 90% of steady state concentration).

times of the year (Figure 5). Moreover, rate constants, calculated separately for all data sets, were very similar implying that seasonal fluctuations in temperature impart a negligible influence on metal kinetics within the clam kidney.

Quantitative Assessments of Metal Abundance

An understanding of contaminant kinetics greatly increase the power of a bio-monitor by allowing qualitative differences, both within and between sites, to be interpreted in more quantitative terms. For example, kinetic estimates of a contaminant's biological concentration factor (BCF), attained at steady state, may, under certain conditions, be used to predict its time-averaged, bioavailable concentration in the water column. In adopting this approach the assumptions are made that the contaminant levels in the bio-monitor are derived from, and are in equilibrium with, levels in the surrounding water. These assumptions may be satisfied by certain hydrophyllic, organic contaminants that are primarily accumulated from water by partitioning across body membranes and rapidly approach steady state. However, trace metals may be derived from several other sources (food, sediments, suspended particulates) besides water and are unlikely to have achieved steady state if ambient levels fluctuate markedly and/or turnover rates within the organism are very slow. In addition, trace metals in water can exist in a variety of chemical forms which may have widely differing biological availabilities and residue kinetics. Such consideration place a number of constraints on the concept of relating tissue levels in a bio-monitor to ambient available levels in the surrounding water. Nevertheless, the approach may provide estimates that are accurate to within an order of magnitude for some metals under certain conditions (see for example, Schulz-Baldes 1974).

Table 4 lists ambient, available estimates for copper, zinc, cadmium, lead and mercury in seawater from Orpheus Island. The data were calculated using the BCF values obtained with *T. crocea* (Figures 4 and 5) and only that for cadmium appears to be unrealistically high. One reason for this is the possibility that *T. crocea* derive their cadmium load predominantly from sources other than water. In keeping with this suggestion, it is noteworthy that high cadmium levels have been reported in *Trichodesmium*, a planktonic species of blue-green algae that blooms prolifically, for several months of the year, along the entire length of the Great Barrier Reef (Jones 1981).

Pulse or episodic inputs of metals into the aquatic environment, coupled with the inability of the bio-monitor to attain equilibrium, is a major failing in the use of BCF estimates to assess background metal availability in the water column. For these reasons monitoring the rate of change of contaminant concentrations in the selected organism (Majori and Petronio 1973, Ritz *et al.* 1982) is an alternative which is referred to in the following section.

Identifying Temporal Trends in Trace Metal Abundance

Quantitative estimates of metal availability, using rates of contaminant change, do not require that levels in the bio-monitor have reached steady state. They do, however require that the kinetics of metal uptake and depuration in the selected organism be known and that some prior knowledge of contaminant levels in its tissues exist. The monitoring strategy involves the repeated collection of samples for analysis at