2004

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Publication details

Pre-print of: Saenger, P & McConchie, D 2004, 'Heavy metals in mangroves: methodology, monitoring and management', *Envis Forest Bulletin*, vol. 4, pp. 52-62.

HEAVY METALS IN MANGROVES: METHODOLOGY, MONITORING AND MANAGEMENT

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Abstract

An extensive study of heavy metals in Australian mangroves has revealed strong regional differences in the concentrations of several metals. The results also indicate that (i) fine textured mangrove sediments are highly efficient and effective sinks for heavy metals; (ii) metal concentrations in mangrove tissues, particularly in young leaves, correlate with concentrations in the sediments; (iii) bioaccumulation of metals occurs in mangroves but differs between species and mangrove tissue types; lead is selectively concentrated in bark and wood of mangroves whereas zinc and copper reach their highest concentrations in young leaves; (iv) mangrove leaf litter can return heavy metals to the environment in a bioavailable form; (v) young leaves are reliable and convenient bioindicators of heavy metal contamination, possibly because their salt-glands are not active and there is no tendency to excrete soluble metal-chloride complexes; and (vi) there are several ways in which the presence of mangroves influences the distribution and dispersion of metals and all have management implications.

From a management point of view, any modification to the mangrove forest is highly likely to alter the chemical and physical conditions in the forest in such a way that the metal uptake is likely to be reversed and a high proportion of the metals that were trapped while the forest existed may be released to the environment. The question is really not whether metals will be released, but how fast and in what form? Hence, removal of a mangrove forest would not only remove a potential pollutant trap that can be very effective in protecting adjacent environments, but it is also very likely to release some of the pollutants that were trapped while the forest existed.

Introduction

Mangroves occur widely throughout Australia and, at some sites, are exposed to elevated heavy metal loads. The value of mangrove communities, and particularly of mangrove forest sediments, as a buffer between potential sources of metalliferous pollutants and marine ecosystems has been noted previously (e.g. Harbison, 1981, 1986; Saenger et al., 1991), but how mangroves respond to the metal load in their environment remains largely unknown. Some work on the response of mangrove seedlings to heavy metal exposure (Montgomery and Price, 1979; Peterson et al., 1979; Walsh et al., 1979; Thomas and Ong, 1984; Chiu et al., 1995; Chen et al., 1995; Wong et al., 1997) has been published, but detailed studies of heavy metals in mangrove ecosystems are rare (Yudman et al., 1988; Mackey et al., 1992; Saenger et al., 1991; Lacerda et al., 1993; Clark et al., 1997, 1998). Mangrove areas are also nursery or breeding grounds for several commercially important species of marine fauna (Saenger, 2002), and because many mariculture operations are sited in or near mangroves, it is important to determine how mangroves respond to metallic pollutants, and to what extent they can shield commercially important species from these pollutants.

To understand the relationship between mangroves and heavy metals, several questions need to be answered, including: How do mangroves respond to high concentrations of metals in their environment? Are heavy metals accumulated in mangroves and, if so, where? Do mangroves return their metal load to the environment in a more or a less bioavailable form? Can mangroves be used to monitor heavy metal concentrations in their environments? How effective are mangroves at shielding the marine environment from metallic pollutants? What are the limits to their buffering capacity? Do mangroves act as a step in a metal biomagnification pathway? How can mangroves be protected from the build-up of heavy metal loads?

As a first step in answering these questions, heavy metal concentrations were compared in this study between mangrove communities from areas (Table 1) where elevated levels are likely and where they are highly improbable. Subsequently, the distribution of copper, lead, zinc and cadmium were determined within the principal parts of common mangrove species and any tendencies towards selective metal accumulation in, or exclusion from, particular parts of the plants were assessed. Currently, the principal pathways for the transfer of metals, the significance of these pathways, and the potential of mangroves as bioindicators of heavy metal contamination in aquatic ecosystems are being examined.

Analytical and Sampling Procedures

Mangrove tissue samples (old leaves, young leaves, wood, bark and fruits were collected where possible) collected in the field were stored in sealed polythene bags and frozen until required for analysis. In the laboratory, the samples were thawed, washed in Milli-Q water, dried at 50°C for 48 hours, weighed and digested in hot concentrated nitric acid and 120 vol hydrogen peroxide; the digests were then boiled down to less than 20 mL, made up to 25 mL with Milli-Q water and stored in acid rinsed vials for later analysis.

The concentrations of copper, lead and cadmium were determined using anodic stripping voltammetry using a “PDV 2000” (Mann & Lintern, 1984). Samples were analysed using 0.2 mL of mangrove tissue digest in 10 mL of electrolyte in the cell of the instrument and a plating time of 100 seconds. All calibrations were achieved by standard spike addition to avoid any possible matrix effects. This method provides excellent sensitivity, precision and accuracy (McConchie et al., 1988; Hall and Vaive, 1991), but there are problems with the analysis of zinc in digests with a high copper content. Hence, all zinc analyses were carried out by standard flame atomic absorption methods (FAAS); copper and lead concentrations in some samples were also analysed by FAAS as an independent check on the analytical data; cadmium concentrations in the digests were all below the detection limit for determination by FAAS.

Replicates for selected samples were used to establish the variance of the data (expressed as coefficients of variation) due to analytical procedures and the results are shown in Figure 1. Variation due to all analytical errors was found to be low, allowing subtle biological differences to be resolved and allowing the analytical technique to be used for monitoring purposes (see also McConchie et al., 1988) as long as the mangroves themselves are useful sentinel organisms.

Sampling procedures were developed using two approaches. First, variations in each tissue type in two single plants were assessed and found to be low; this approach integrates variation for individual plants and analytical error. The second approach involved sampling each tissue type from a series of replicate trees at several sites; these data integrate sampling variation within and between individual trees and analytical error and consequently, show a higher variance. By these approaches, the three likely sources of experimental error have been considered and quantified.

Multiple samples taken from two *Avicennia* trees (one from near the Wynnum Tip and the other from near the Wynnum sewer outfall) to determine the natural variation in single trees showed that the concentration of Cu and Zn could be expected to vary by about 10% in different leaf samples from a single tree whereas the concentration of lead may vary by about 20%. In the wood of the trees the variation is much higher at 20 - 30% at the sewer outfall but is similar to variation in the leaves at the Wynnum tip site. This finding suggests that discharge from the sewer may have changed over time and that wood samples of different age reflect this in their high variance, but there may also be other reasons. The metal content, particularly Cu, in the bark of the trees from the sewer outfall site is also much more variable than in the bark of trees from the tip site. Overall, it is evident that, at most sites, the natural variation in the concentration of trace metals in *Avicennia* tissues will normally be about 10% for Cu and Zn and about 20% for Pb, but these values may increase to about 20% and 30% respectively at some sites. Hence, it is reasonable to assume that there are real differences between sites if the difference in the concentration of any metal in the mangrove tissues is greater than about 25%.

Monitoring heavy metal concentrations in mangrove sediments and plant tissues

Heavy metal distribution in different plant tissues of different species

Mangrove tissue samples were collected from numerous sites around Australia, including locally polluted (Georges River, Sydney and Brisbane River, Brisbane) and pristine (Esk River within Broadwater National Park) localities (Table 1). Regional averages for metal concentrations in different tissues of each plant type (Table 2) can be used to evaluate differences in metal uptake between plant species and tissue types because at each site the same number of samples of each type of tissue was collected; i.e. the fact that different sites in each area have different metal loads does not invalidate the data.

In *Avicennia marina,* from all areas there is a clear tendency for Cu and Zn to be more concentrated in young leaves than in old leaves. *Aegiceras corniculatum* and *Rhizophora stylosa* show the same tendency although it is not as strong for Zn in *Aegiceras. Hibiscus tiliaceus, Excoecaria agallocha, Bruguiera gymnorhiza* and *Ceriops tagal* show no significant difference between metal concentrations in old and young leaves.

In *Bruguiera gymnorhiza,* Cu has a fairly uniform distribution in all tissue types but data are presently available only for one area, which is near pristine, and all metal concentrations are low. Pb may be slightly more concentrated in the wood and the bark and Zn is distinctly concentrated in the bark; both metals are fairly uniformly distributed in the other tissues.

In *Ceriops tagal,* there is no significant difference between old and young leaves; and all metals are usually more concentrated in the bark than in the leaves and slightly less concentrated in the wood.

In *Excoecaria agallocha,* Cu and Pb tend to be more concentrated in the bark and the wood than in the leaves, but Zn is more abundant in the leaves; there are, however, few data.

In *Hibiscus tiliaceus,* Zn tends to be uniformly distributed between tissue types, whereas Cu is slightly more abundant in the bark and the wood than in the leaves, and Pb is distinctly more abundant in the wood and the bark than in the leaves; there is no consistent difference between the metal content in the wood and the bark.

In *Avicennia, Aegiceras* and *Rhizophora,* Cu is usually most abundant in young leaves followed by the old leaves and bark, with the wood and fruit having the least. Pb is most abundant in the bark followed by the other tissue types, which have similar concentrations; wood from *Avicennia* and *Aegiceras* from the Esk River is an exception in that the concentration of Pb in the wood of these trees is similar to that in the bark. Zn tends to be most abundant in bark of the trees followed by young leaves; the concentration in the old leaves and the fruit is lower and the concentration in the wood is the lowest.

In all species examined, tree height does not appear to influence metal concentrations in mangrove tissues although based on limited data, seedlings tend to have elevated concentrations relative to more mature plants.

Heavy metal concentrations at polluted and non-polluted sites

The trace metal concentrations in mangroves are normally lower than concentrations in the sediments in the mangrove forest, suggesting that there is little value in analysing the mangrove tissues instead of the sediment. However, mangrove tissues have the advantage that metal concentrations are not affected by differences in sediment texture or mineralogy between sites. Because metals are largely concentrated in the fine fraction of sediment and the grain size distribution is largely controlled by hydrodynamic processes rather than pollution, the metal load in sediment can be more a function of hydrodynamic conditions than pollutant loading unless the data are grain size normalised (e.g. see Förstner, 1989, Table 3-2, Fig. 3-3); the size normalisation process itself has problems and there is not yet any agreement on how best to achieve it (although most investigators agree that it must be done). In this sense, analysing mangrove tissues has some advantages. It may also have an advantage in that the metal content of the mangroves is likely to reflect a time averaged metal load, whereas if a sediment is exposed to metal concentrations that vary over time, the total metal load in the sediment and its distribution can be changed by physical, chemical, microbial and faunal activity that may have nothing to do with the metal supply (Förstner, 1989; Lewis and McConchie, 1994; Clark et al., 1997).

Generally, the metal content of mangrove tissues, particularly *Avicennia* and *Aegiceras* (too few data to be certain for the others), increases consistently with increasing environmental metal loads. This can be seen in regional comparisons (Table 2) and also in trends within areas (e.g. at different sites in the Georges or Brisbane Rivers). Zn and Cu concentrations show the trends particularly well and the concentration of these metals in mangrove tissues correlates with their concentrations in sediment (Figs. 2 and 3). The Pb concentration (Fig. 4) is somewhat different in that it shows a tendency to concentrate in the bark and wood of the mangroves and the concentration seems to be more strongly controlled by the proximity of the tree to a major road; this probably shows the influence of particulate lead from the road (vehicle exhausts) getting trapped on the damp bark or on its rough surface; with the phasing out of leaded fuels, this selective concentration may be expected to decrease over time. Cd concentrations are too near our detection limit to be certain of major trends.

The high standard deviation in the regional averages (particularly Georges River and Brisbane River) for each tissue type reflects the big range in the degree of contamination of sites in each of the regions. At some sites (e.g. Mangrove Lane, Sydney) the pollution level is very high and this is reflected in the metal loads in the mangroves. Hence, it seems clear that metal concentrations, particularly in young leaves, can be used as a time averaged measure of heavy metals in the mangrove environment on both regional and more local scales. Near the Wynnum Tip where several trees have been sampled, a decrease in metal concentrations away from the tip face was evident (Saenger et al., 1991) and it would appear that in some areas the metal content in mangrove tissues can reflect differences in environmental metal loads on a scale down to a few tens of metres.

Monitoring of heavy metals in mangroves: a case study

Heavy metals in mangrove tissues provided one of the indicators used to monitor the effects of the Queensland Aluminium Limited alumina refinery in Gladstone, Queensland (Fig. 5) on adjacent ecosystems. This study was designed to determine the long-term effect of discharges from the red mud and ash ponds at the refinery on adjacent estuarine communities (McConchie et al., 1996). Several sites at varying distances from discharges from the red mud ponds and the ash ponds were sampled; at each site, water, sediment and mangrove tissues were collected and analysed.

Trace element data for the mangrove tissue samples (Table 3) showed some increase in the concentrations of fluoride, aluminium, copper, gallium and arsenic in South Trees Inlet samples relative to samples from the control site in Wild Cattle Creek but the difference is small and, with the exception of Al, the data reveal no trends that could be related to proximity to the red mud pond or the ash pond outfalls. Mangrove tissue samples with notably high concentrations of individual trace elements occur with similar frequency at all control and survey sample sites. On average, the trace element concentrations in the mangrove samples are slightly higher than values obtained for samples from the Esk River in N.S.W. (the Esk River catchment is largely in a National Park) and well below concentrations obtained for most samples from the Brisbane River estuary and from the Georges River in Sydney (c.f. Table 2); this finding is consistent with the sediment and water data that indicate that the discharges from the ash and red mud ponds are having no significant long-term effects.

The South Trees Inlet and Wild Cattle Creek sites are also a good illustration of the effect of grain size on trace metal concentrations in sediments. Sediments are dominantly sandy in Wild Cattle Creek and have low metal loads. Channel samples in South Trees Inlet are dominated by coarse sand and grit and have very low metal loads. Intertidal sediments in South Trees Inlet, on the other hand, are muddy and have much higher metals loads (McConchie et al., 1996).

Management of heavy metals within mangrove ecosystems

Once heavy metals have entered into a mangrove community, they are readily trapped by the mangrove forest sediments (Harbison, 1981; 1986; Silva et al., 1990; Clark et al., 1997). Metals are initially adsorbed to fine grained surficial sediments and most are later bound more permanently as metal sulphides in the anoxic horizon beneath the sediment surface. Metals bound as metal sulphides are largely immobilised although they may be available for mangrove root uptake in the oxidised rhizosphere (Youssef and Saenger, 1996) or they may be released during physical or biological disturbance of the sediment (Clark et al., 1997, 1998). Consequently, mangrove sediments help to prevent the heavy metals from entering the adjacent marine ecosystems. Some metals taken up by mangroves could enter marine ecosystems in an organic form through litterfall but heavy metal concentrations in leaf litter from *Avicennia* are generally low (Table 4) and the plant material would be rapidly dispersed by tidal movement.

The protection of marine systems against terrestrial pollution input afforded by mangrove forests was investigated at the municipal garbage dump at Wynnum, south-east Queensland (Saenger et al., 1991). Here, a garbage dump for household and minor industrial wastes was established on saltflats at the landward margin of a mangrove forest bordering Moreton Bay. Although the wastes were contained by bund walls, leakage and subsurface drainage allowed leachates with high heavy metal concentrations to enter the mangroves; a substantial quantity of metallic waste was also found dumped in the mangrove forest outside the bund walls. Two transects running from the tip face through the mangroves to their seaward margins were established, and both sediment and mangrove tissue samples were collected and analysed. The results (Figs. 6 and 7) show that heavy metal concentrations in the sediments and the mangroves decreased rapidly in a seaward direction, illustrating the rapid immobilisation that occurred within the mangrove forest. Although seasonal shifts in the watertable, and changes in the redox profile at the site did cause some redistribution of trace metals in the sediment (Clark et al., 1997, 1998), the capacity of mangroves and their sediments to store heavy metals was not exceeded. Nevertheless, as a precautionary measure, the garbage dump was closed and sealed to ensure that the marine fisheries of Moreton Bay did not become adversely affected.

Discussion and Conclusions

In summary, it was found that fine textured mangrove sediments are highly efficient and effective sinks for heavy metals and metal concentrations in mangroves, particularly in young leaves, correlate with the concentrations in the sediments. Some modest bioaccumulation of metals occurs in mangroves but varies between species and different plant parts, with lead being selectively concentrated in bark and wood of mangroves, whereas zinc and copper reach their highest concentrations in young leaves. In *Avicennia marina,* the root epidermis has been found to form a major barrier to Pb (MacFarlane and Burchett, 2000).

Mangrove leaf litter can return heavy metals to the environment in a bioavailable form but the amounts of metals involved are low, the leaf litter is usually rapidly dispersed, and the rate of metal release from the leaf litter is low.

Young leaves are reliable and convenient bioindicators of heavy metal contamination. Although in most biota exposed to elevated concentrations of heavy metals, either accumulation occurs and tissue concentrations increase with the age of the tissue or the concentrations in the tissue remain fairly constant. However, most of the mangroves so far examined show elevated metal concentrations in young rather than old leaves, a reverse bioaccumulation. Two observations may hold the key to this most unusual feature: First, the species with the greatest differentials in concentrations between young and old leaves are those mangroves with salt secreting glands, capable of actively pumping chlorides from the leaves. Second, those metals showing the greatest differentials in concentrations are those, such as copper and zinc that readily form soluble chloride complexes in aqueous solution. MacFarlane and Burchett (1999) have shown that the salt-secreting *A. marina* actively extrudes zinc. Thus, it is tempting to suggest that young leaves, which are less actively excreting chlorides because they are expanding in size are consequently, but temporarily, concentrating metal ions within their tissues.

There are several ways in which the presence of mangroves influences the distribution and dispersion of metals and all have management implications:

a) The current baffle provided by mangrove forests promotes the deposition of fine grained sediments that have a much greater metal binding capacity than coarser sediments. Hence, mangrove muds normally have a higher metal content than nearby sediment that is not in the mangrove forest. In this way a mangrove forest will act as a trap for any fine (potentially metal loaded) sediment washed off the land; this is particularly significant for mangroves near major roads where there is a large source of fine particulate lead from vehicle emissions; mangrove forests will trap this particulate lead very well as indicated by some of the data.

b) Sulphate reducing bacteria, which are commonly much more abundant in sediment in mangrove forests than in adjacent more physically unstable areas, cause the sediment to become reducing at or slightly below the sediment surface and increase the availability of sulphide ions. The presence of the sulphide ions, in particular, helps trap metals because most metal sulphides have a very low solubility. If mangrove forests are ever cleared it is likely that physical disturbance of these sulphidic sediments and any surface drying would result in the decomposition of many of the sulphides and the metals that were present as sulphides would be released to the environment; the oxidation of the sulphides also releases acid (sulphuric acid, as in acid sulphate soils) and this acid has the capacity to leach more metals from the sediment and transport them to adjacent water bodies.

c) Mangrove forests are also excellent environments for accumulating organic matter (both material washed into the forest and trapped, and fragments of dead mangrove) and as this organic matter decomposes it produces breakdown products that can trap metals both by adsorption and by chelation.

d) Mangroves incorporate some metals into their tissues but, even at polluted sites, the concentrations attained are not exceptionally high. However, the metal content of many mangroves sampled in this study is notably higher than would normally be expected in common land plants grown in uncontaminated soils.

e) Various faunal species that are found in mangrove forests may take up metals.

From a management point of view, items (a) and (b) above are the most important because any modification to the mangrove forest is highly likely to alter the chemical, physical and biological conditions in such a way that metal uptake can be reversed and a high proportion of the metals that were trapped while the forest existed may be released to the environment. The question is really not whether they will be released, but how fast and in what form?

Given the propensity of mangroves and their sediments to act as a sink for heavy metals, from a management perspective it becomes imperative to minimise or avoid heavy metal input into mangrove systems. In particular, planners should avoid municipal garbage dumps being sited near mangroves (Clark 1998) and keep industrial effluents separate from sewage; well treated sewage effluent with a low metal content does not appear to have an adverse impact on mangroves (Nedwell, 1974; Clough et al., 1983; Kelly, 1995). Perhaps even more importantly, once heavy metals have entered mangrove systems, minimising sediment disturbance or damage to the mangrove forest that could result in changed redox conditions becomes essential if potential release of the metals to the adjacent marine environment is to be avoided.

Hence, removal of a mangrove forest would not only remove a potential pollutant trap that can be very effective in protecting adjacent environments, but it is also very likely to release some of the pollutants that were previously trapped while the forest existed.

Acknowledgements

This study was initiated by an Australian Research Council grant from 1988-91, which is gratefully acknowledged. Further support has been obtained from QAL, Brisbane Port Authority and the Environmental Analysis Laboratory at Southern Cross University.

References

Chen, G.Z., S.Y. Miao, N.F.Y. Tam, Y.S. Wong, S.H. Li and C.Y. Lan, 1995. Effects of synthetic wastewater on young *Kandelia candel* plants growing under greenhouse conditions. Hydrobiologia 295:263-273.

Chiu, C.Y., F.S. Hsiu, S.S. Chen and C.H. Chou, 1995. Reduced toxicity of Cu and Zn to mangrove seedlings in saline environments. Bot. Bull. Acad. Sin. 36:19-24.

Clark, M.W., 1998. Management implications of metal transfer pathways from a refuse tip to mangrove sediments. Science of the Total Environment 222:17-34.

Clark, M.W., D. McConchie, D.W. Lewis and P. Saenger, 1998. Redox stratification and heavy metal partitioning in *Avicennia* dominated mangrove sediments: a geochemical model. Chemical Geology 149:147-171.

Clark, M.W., D. McConchie, P. Saenger and M. Pillsworth, 1997. Hydrological controls on copper, cadmium, lead and zinc concentrations in an anthropogenically polluted mangrove ecosystem, Wynnum, Brisbane. J. Coastal Res. 13:1150-1158.

Clough, B.F., K.G. Boto and P.M. Attiwill, 1983. Mangroves and sewage: a re-evaluation. In: Teas, H.J. (Ed.), Biology and Ecology of Mangroves. Dr. W. Junk Publishers, Boston, pp. 151-161.

Förstner, U., 1989. Contaminated sediments. Lecture notes in Earth Sciences Vol. 21, Springer Verlag, Berlin, 157 pp.

Hall, G.E.M. and J.E. Vaive, 1991. Field analysis using an anodic stripping voltammeter. Explore 70:18-20.

Harbison, P., 1981. The case for the protection of mangrove swamps: geochemical considerations. Search 12:273-276.

Harbison, P., 1986. Mangrove muds - a sink or source for trace metals. Mar. Pollut. Bull. 17:246-250.

Kelly, T., 1995. An investigation into the ability of mangroves to utilise nutrients from domestic sewage effluent. Unpubl. Thesis, Southern Cross University, 116 pp.

Lacerda, L.D., C.E.V. Carvalho, K.F. Tanizaki, A.R.C. Ovalle and C.E. Rezende, 1993. The biogeochemistry and trace metals distribution of mangrove rhizospheres. Biotropica 25:252-257.

Lewis, D.W. and D.M. McConchie, 1994. Practical sedimentology. Chapman & Hall, New York, XXX pp.

MacFarlane, G.R. and M.D. Burchett, 1999. Zinc distribution and excretion in the leaves of the grey mangrove, *Avicennia marina* (Forsk.) Vierh. Environmental and Experimental Botany 41:167-175.

MacFarlane, G.R. and M.D. Burchett, 2000. Cellular distribution of copper, lead and zinc in the grey mangrove, *Avicennia marina* (Forsk.) Vierh. Aquatic Botany 68:45-59.

Mackey, A.P., M. Hodgkinson and R. Nardella, 1992. Nutrient levels and heavy metals in mangrove sediments from the Brisbane River, Australia. Mar. Pollut. Bull. 24:418-420.

Mann, A.W. and M. Lintern, 1984. Field analysis of heavy metals by portable digital voltammeter. J. Geochemical Explor. 22:333-348.

McConchie, D., P. Saenger and N. Holmes, 1996. An environmental assessment of the Boyne River Estuary. In: Piorewicz, J. (Ed.), Proceedings of the Workshop on the Boyne River Estuary, Gladstone, July 1996, Central Queensland University Press, pp. 84-109.

McConchie, D., P. Saenger and R. Fawkes, 1996. An environmental assessment of the use of seawater to neutralise bauxite refinery wastes. In: Ramachandran, V. and C.C. Nesbitt (Eds.), Second international symposium on extraction and processing for the treatment and minimization of wastes, The Minerals, Metals & Materials Society, pp. 407-416.

McConchie, D.M., Mann, A.W., Lintern, M.J., Longman, D., Talbot, V., Gabelish, A.J. and Gabelish, M.J. 1988. Heavy metals in marine biota, sediments, and waters from the Shark Bay area, Western Australia. J. Coastal Res. 4:51-72.

Montgomery, J.R. and M.T. Price, 1979. Release of trace metals by sewage sludge and the subsequent uptake by members of a turtle grass mangrove ecosystem. Environ. Sci. & Technol. 13:546-549.

Nedwell, D.B., 1974. Sewage treatment and discharge into tropical coastal waters. Search 5:197-190.

Peterson, P.J., M.A. Burton, M. Gregson, S.M. Nye, and E.K. Porter, 1979. Accumulation of tin by mangrove species in West Malaysia. Science of the Total Environment 11:213-221.

Saenger, P., 2002. Mangrove ecology, silviculture and conservation. Kluwer Academic Publishers, 360 pp.

Saenger, P., D. McConchie and M. Clark, 1991. Mangrove forests as a buffer zone between anthropogenically polluted areas and the sea. In: Arakel, A.V. (Ed.), Proceedings of 1990 Workshop on Coastal Zone Management, Yeppoon, Queensland, pp. 280-299.

Silva, C.A.R., L.D. Lacerda and C.E. Rezende, 1990. Metals reservoir in a red mangrove forest. Biotropica 22:339-345.

Thomas, C. and Ong, J.E., 1984. Effect of heavy metals zinc and lead on *Rhizophora mucronata* Lam. and *Avicennia alba* Bl. seedlings. In: Soepadmo, E., A.N. Rao and D.J. McIntosh (Eds.), Proceedings of the Asian Symposium Mangrove Environments – Research and Management, UNESCO, pp. 568-574.

Walsh, G.E.R., K.A. Ainsworth and R. Rigby, 1979. Resistance of red mangrove (*Rhizophora mangle L.)* seedlings to lead, cadmium and mercury. Biotropica 11:22-27.

Wong, Y.S., N.F.Y. Tam and C.Y. Lan, 1997. Mangrove wetlands as wastewater treatment facility: a field trial. Hydrobiologia 352:49-59.

Youssef, T. and P. Saenger, 1996. Anatomical adaptive strategies and rhizosphere oxidation in mangrove seedlings. Aust. J. Bot. 44:297-313.

Yudman, W., L. Changyi, H. Jiandong and L. Yuling, 1988. Removal of heavy metals from sediments by mangroves in Juilong estuary, Xiamen Harbour, China. Water Sci. Tech. 20:55-62.

Table 1. Location and characteristics of sampled sites in eastern Australia.

Location	**Site characteristics**
South-east Queensland	
Brisbane River	Numerous sites sampled from the mouth of the river to the University of Queensland
Wynnum Tip	Municipal garbage producing polluted leachate
Wynnum Sewage Outfall	Several organically polluted sites sampled
Central Queensland	
South Trees Inlet	Eleven sites sampled ranging from pristine to possibly slightly polluted
New South Wales	
Georges River, Sydney, NSW	Several sites sampled ranging from heavily to slightly polluted
Cooks River, Sydney	Near Airport
Salt Pan Creek, Sydney	At bridge near Henry Lawson Drive
Oyster Bay, Sydney	Several sites sampled including near the garbage tip near Kareela Golf Course
Esk River, NSW	Several sites sampled every 0.5 km for 2.5 km upstream from its junction with the Clarence River; river is entirely within a National Park and pristine

Table 2. Regional means (and standard deviations) of metal concentrations in different tissues of various mangrove species. With the exception of *Rhizophora* and *Excoecaria* samples from the mouth of the Brisbane River, where n = 2, sample sizes were 20 throughout.

Sample Type	**Cu**	**Pb**	**Zn**	**Cd**
Georges River, NSW				
Avicennia marina				
Young leaves	16.6 (10.2)	2.9 (1.3)	35.9 (16.7)	≤0.01
Old leaves	10.9 (6.9)	3.2 (1.2)	25.2 (12.9)	≤0.01
Wood	5.5 (2.4)	3.7 (1.6)	15.6 (9.4)	≤0.01
Bark	16.3 (7.7)	12.2 (5.8)	54.9 (23.5)	0.04
Fruit	7.7 (2.7)	4.1 (2.1)	31.1 (7.0)	0.01
Aegiceras corniculatum				
Young leaves	12.1 (5.9)	3.4 (0.9)	43.7 (12.2)	≤0.01
Old leaves	8.4 (4.5)	4.0 (1.3)	30.4 (10.5)	≤0.01
Wood	6.2 (2.5)	3.0 (1.2)	16.9 (8.1)	≤0.01
Bark	14.4 (5.1)	15.7 (6.1)	50.7 (40.3)	0.03 (0.02)
Fruit	8.8 (3.6)	2.1 (0.9)	23.4 (8.2)	0.03 (0.04)
Esk River, NSW				
Avicennia marina				
Young leaves	6.8 (1.8)	3.0 (0.7)	20.9 (6.3)	≤0.01
Old leaves	4.7 (1.5)	3.8 (0.8)	17.4 (5.7)	≤0.01
Wood	4.3 (0.8)	14.1 (4.0)	15.6 (11.4)	≤0.01
Bark	6.5 (1.7)	11.5 (3.4)	17.6 (5.3)	≤0.01
Aegiceras corniculatum				
Young leaves	5.1 (0.9)	2.4 (0.8)	20.7 (4.4)	≤0.01
Old leaves	3.6 (0.9)	3.6 (1.1)	13.7 (2.5)	≤0.01
Wood	5.7 (2.1)	7.5 (3.3)	9.9 (4.2)	≤0.01
Bark	5.9 (2.1)	7.5 (2.1)	12.6 (4.0)	≤0.01
Hibiscus tiliaceus				
Young leaves	8.3 (2.5)	3.6 (1.1)	23.5 (3.5)	≤0.01
Old leaves	7.5 (2.1)	4.2 (0.9)	24.2 (5.4)	≤0.01
Wood	13.3 (1.3)	11.1 (1.8)	20.8 (4.6)	≤0.01
Bark	15.8 (2.0)	11.5 (1.7)	25.5 (8.4)	≤0.01
Excoecaria agallocha				
Young leaves	13.3 (3.5)	4.3 (0.6)	38.5 (10.3)	≤0.01
Old leaves	10.5 (3.2)	5.0 (1.3)	34.3 (6.0)	≤0.01
Wood	20.5 (4.5)	15.1 (2.6)	13.7 (7.4)	≤0.01
Bark	21.4 (4.9)	13.0 (3.7)	23.5 (8.9)	≤0.01
Bruguiera gymnorhiza				
Young leaves	7.6 (0.6)	2.5 (0.7)	16.4 (2.4)	≤0.01
Old leaves	7.2 (0.4)	3.2 (0.4)	16.8 (2.5)	≤0.01
Wood	4.8 (1.2)	7.2 (3.7)	22.4 (8.6)	≤0.01
Bark	6.6 (1.1)	7.6 (1.1)	35.5 (10.4)	≤0.01
Fruit	6.1 (0.8)	4.8 (0.6)	8.8 (2.5)	≤0.01

Table 2 contd.

Sample Type	**Cu**	**Pb**	**Zn**	**Cd**
Brisbane River, Qld				
Avicennia marina				
Young leaves	18.3 (6.8)	2.4 (1.2)	34.6 (10.7)	0.01 (0.02)
Old leaves	12.2 (5.3)	2.7 (1.2)	22.2 (8.2)	≤0.01
Wood	5.0 (2.9)	2.6 (1.4)	13.9 (7.4)	≤0.01
Bark	14.0 (5.4)	11.6 (4.8)	47.3 (13.3)	0.02 (0.02)
Fruit	6.8 (2.5)	2.4 (0.9)	28.1 (7.1)	0.03 (0.01)
Aegiceras corniculatum				
Young leaves	20.4 (5.4)	4.7 (2.1)	38.9 (10.4)	≤0.01
Old leaves	10.7 (4.2)	6.1 (3.0)	28.4 (10.9)	≤0.01
Wood	6.2 (1.9)	3.5 (1.7)	18.9 (5.9)	≤0.01
Bark	14.9 (7.2)	16.4 (5.3)	37.0 (17.5)	0.04 (0.02)
Fruit	9.7 (3.9)	2.2 (1.0)	18.4 (4.0)	0.02 (0.02)
Rhizophora stylosa				
Young leaves	19.6	1.6	29.2	≤0.01
Old leaves	13.3	2.8	22.0	0.04
Wood	10.3	3.0	18.0	0.03
Bark	19.4	9.5	28.9	0.04
Excoecaria agallocha				
Young leaves	9.2	2.8	16.7	≤0.01
Old leaves	8.7	4.2	9.5	0.04
Wood	10.3	3.5	20.3	0.02
Bark	8.2	1.8	16.5	0.05
Ceriops tagal				
Young leaves	13.4 (4.6)	4.0 (3.3)	20.1 (3.8)	0.02 (0.02)
Old leaves	11.5 (4.6)	3.6 (1.3)	21.8 (9.9)	0.02 (0.02)
Wood	9.1 (1.8)	2.8 (1.5)	17.6 (4.1)	0.02 (0.01)
Bark	17.8 (4.4)	10.4 (3.8)	30.4 (6.8)	0.03 (0.01)
South Trees Inlet, Gladstone, Qld.				
Avicennia marina				
Young leaves	3.7 (1.3)	1.0 (0.1)	11.0 (1.7)	≤0.01
Old leaves	3.2 (0.9)	1.0 (0.2)	9.6 (2.1)	≤0.01
Wood	2.0 (0.3)	0.7 (0.1)	4.3 (0.7)	≤0.01
Bark	5.6 (1.2)	1.0 (0.2)	20.2 (5.2)	≤0.01
Rhizophora stylosa				
Young leaves	2.3 (0.6)	1.0 (0.2)	5.7 (1.9)	≤0.01
Old leaves	2.1 (0.4)	1.0 (0.1)	4.4 (1.3)	≤0.01
Wood	1.7 (0.4)	0.8 (0.1)	2.4 (0.6)	≤0.01
Bark	2.9 (0.6)	1.1 (0.3)	6.4 (2.2)	≤0.01

Table 3. Heavy metal concentrations (in mg/kg) in young leaves of *Avicennia marina* around QAL, Central Queensland. Location of numbered sites are shown in figure 6.

Site No.	**F**	**Al**	**Ni**	**Cu**	**Zn**	**Ga**	**As**	**Ba**	**Pb**
1	22	156	1.9	2.6	12.9	7.3	4.2	28.5	0.9
2	18	286	1.7	4.4	13.1	7.4	5.2	26.2	0.9
3	21	417	1.8	2.8	11.2	5.9	4.8	25.0	1.0
4	21	286	1.6	6.6	12.6	8.2	7.8	30.9	1.3
5	22	256	2.1	6.0	8.9	8.8	11.3	28.7	1.3
6	22	131	1.6	4.0	9.6	6.5	6.1	20.9	1.1
7	18	293	1.8	3.5	10.3	7.5	9.2	25.0	1.0
8	17	127	1.5	3.0	10.4	6.0	6.0	26.7	1.0
9	16	69	1.5	3.0	10.8	6.2	4.9	24.1	1.0
10	14	87	1.6	2.7	12.6	5.4	4.0	21.3	0.0
11	14	88	1.4	2.4	7.9	7.0	3.8	27.9	0.9

At all sites V <0.1; Cr <0.1; Mo <0.1; Cd <0.05; W <1; Hg < 0.01.

Table 4. Heavy metal concentrations (mg/kg) in leaf litter from *Avicennia marina* from the mouth of the Brisbane River, Queensland.

Metal	Mean concentration
Cu	32.3
Pb	4.6
Zn	68.7
Cd	<0.01

LEGENDS FOR FIGURES 1-8

Fig. 1. Relationship of the coefficient of variation (%) and the mean metal concentration in leaves of *Avicennia marina.*

Fig. 2. Regression of zinc concentrations (in mg/kg) in sediments (Zn-S) and young leaves of *Avicennia marina* (Zn-L).

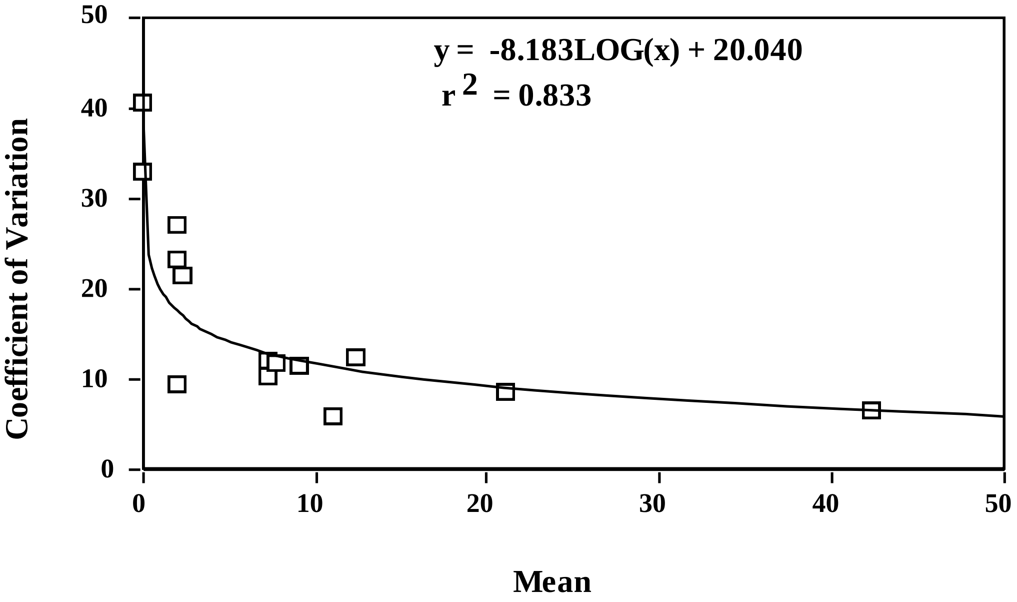
Fig 3. Regression of copper concentrations (in mg/kg) in sediments (Cu-S) and young leaves of *Avicennia marina* (Cu-L).

Fig. 4. Regression of lead concentrations (in mg/kg) in sediments (Pb-S) and young leaves of *Avicennia marina* (Pb-L).

Fig. 5. Locality Map of sampling sites 1 to 11 around the Queensland Aluminium Limited refinery in Central Queensland.

Fig. 6. Heavy metal concentrations (in mg/kg) in mangrove sediments of transects 1 and 2 at the Wynnum Tip site near the mouth of the Brisbane River, south-east Queensland.

Fig. 7. Heavy metal concentrations (in mg/kg) in mangrove leaves of transects 1 and 2 at the Wynnum Tip site.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r^2 = 0.833
Coefficient of Variation
Mean
0
10
20
30
40
50
0
10
20
30
40
50

Figure 1

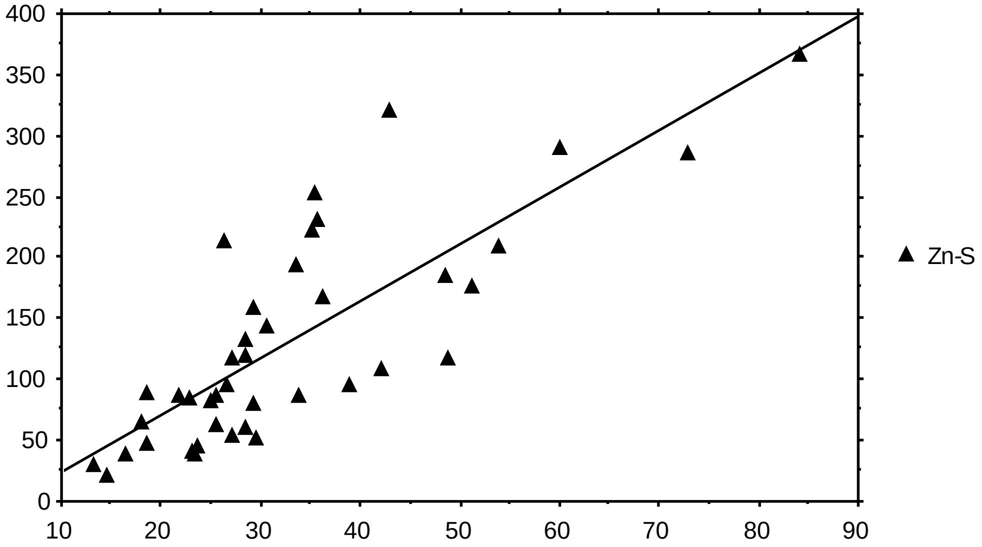


Figure 2

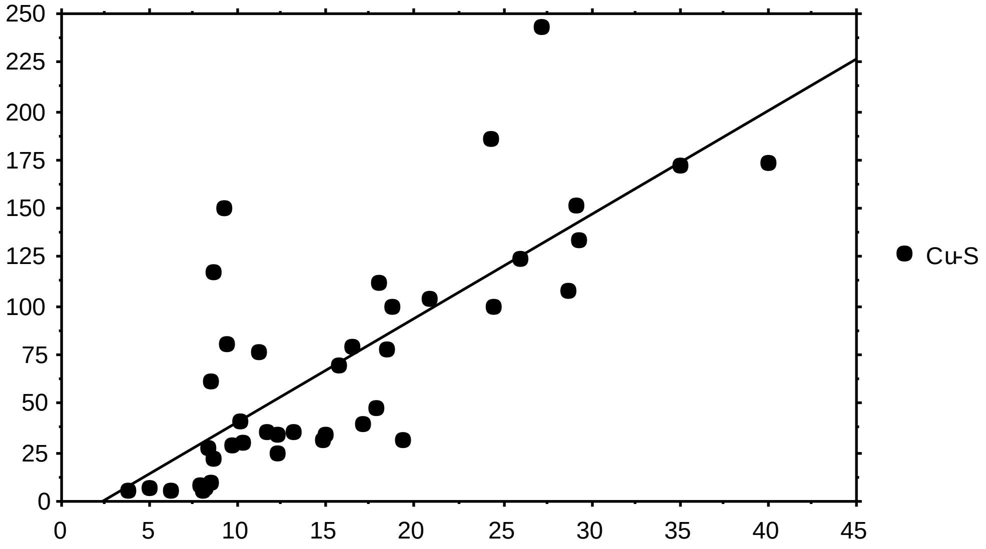


Figure 3

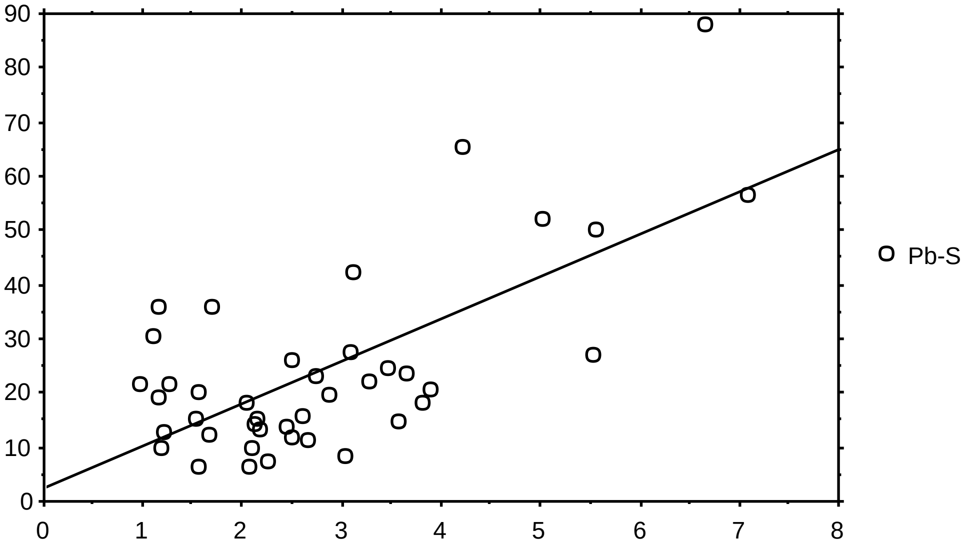


Figure 4

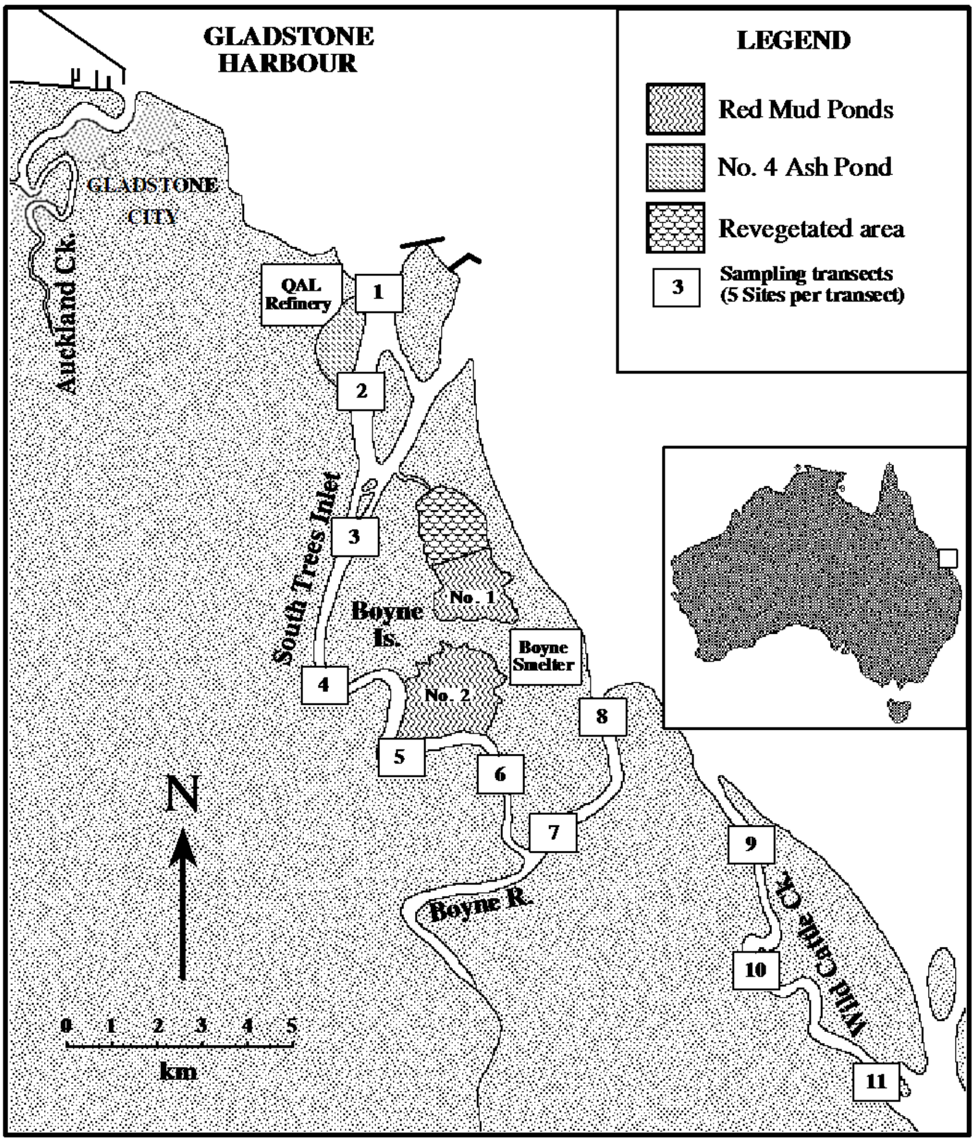
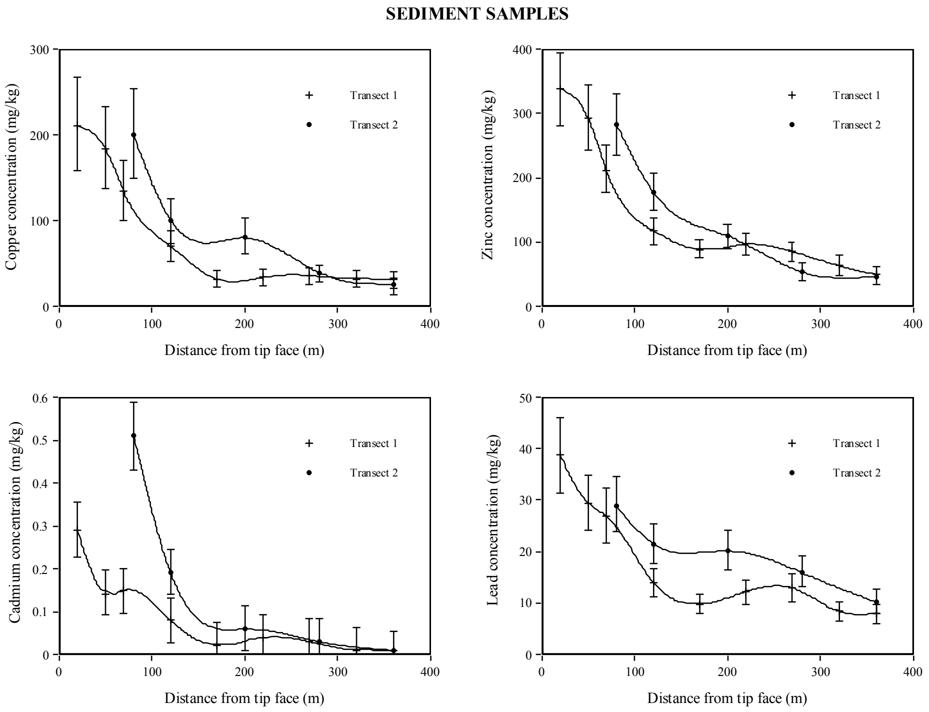
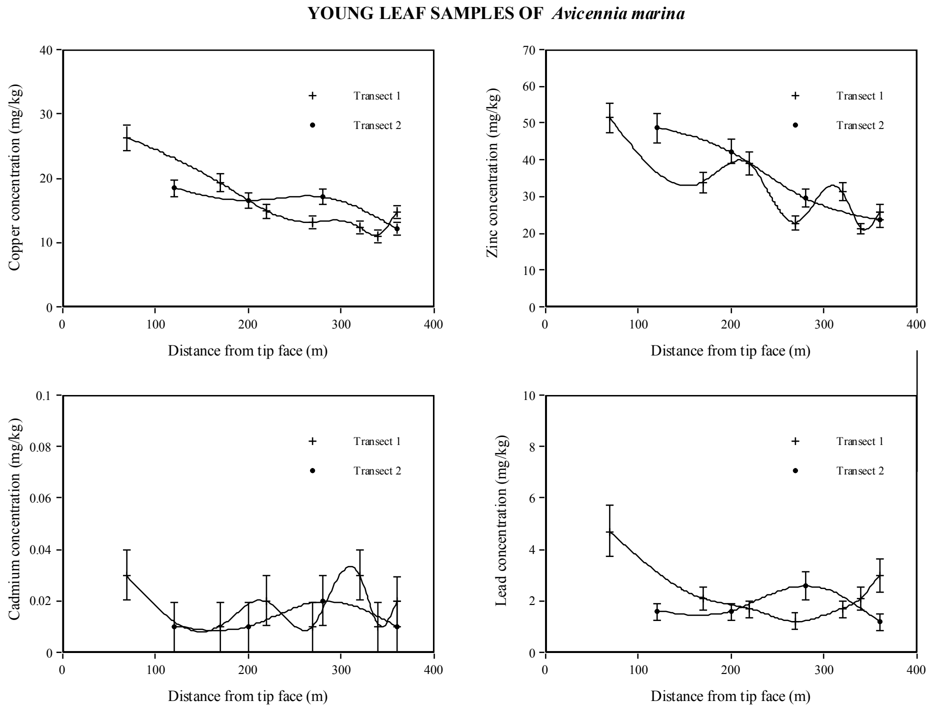

GLADSTONE HARBOUR
LEGEND
Red Mud Ponds
No. 4 Ash Pond
Revegetated area
3
Sampling transects (5 Sites per transect)
GLADSTONE CITY
Auckland Ck.
QAL Refinery
1
2
South Trees Inlet
3
No. 1
Boyne Is.
Boyne Smelter
4
No. 2
8
5
6
7
Boyne R.
9
Wild Cattle Ck.
10
11
N
0 1 2 3 4 5
km

Figure 5



SEDIMENT SAMPLES

Figure 6



YOUNG LEAF SAMPLES OF *Avicennia marina*

Figure 7