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Impacts of gold mine waste disposal on deepwater fish in a pristine tropical marine system

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Abstract

Little is known about the impacts of mine waste disposal, including deep-sea tailings, on tropical marine environments and this study presents the first account of this impact on deepwater fish communities. The Lihir gold mine in Papua New Guinea has deposited both excavated overburden and processed tailings slurry into the coastal environment since 1997. The abundances of fish species and trace metal concentrations in their tissues were compared between sites adjacent to and away from the mine. In this study (1999–2002), 975 fish of 98 species were caught. Significantly fewer fish were caught close to the mine than in neighbouring regions; the highest numbers were in regions distant from the mine. The catch rates of nine of the 17 most abundant species were lowest, and in three species were highest, close to the mine. There appears to be limited contamination in fish tissues caused by trace metals disposed as mine waste. Although arsenic (several species) and mercury (one species) were found in concentrations above Australian food standards. However, as in the baseline (pre-mine) sampling, it appears they are accumulating these metals mostly from naturally-occurring sources rather than the mine waste.

Keywords: Submarine tailings; Trace metals; Deepwater fish; Serranidae; Lutjanidae; Carangidae

1. Introduction

The disposal of mine waste into seas and oceans is considered an acceptable practice in many parts of the world (Ellis and Ellis, 1994), despite our relatively poor knowledge of the fate of these potentially toxic materials and their impacts on biological communities. Concentrated tailings waste produced during ore processing (e.g. Powell and Powell, 2001; Elberling et al., 2003; Ellis et al., 1995), which contain high concentrations of potentially toxic trace metals, are mostly disposed into the sea at depth (Ellis et al., 1995). The effect is potentially similar to spills from tailings dams or mine drainage (e.g. Pain et al., 1998; Suner et al., 1999; Barry et al., 2000; Mateos, 2001; Pirrie et al., 2003). Another form of mine waste dumped into the sea is large volumes of excavated overburden, which can change the sea bed and release heavy elements that occur naturally in the ore body.

The main ecological issues about disposal of mine waste into the marine environment are (i) the potential uptake of bioavailable trace metals into tissues of marine organisms (e.g. Swales et al., 1998; Suner et al., 1999; Mol et al., 2001); (ii) bio-accumulation of these metals through food webs (e.g. Ellis et al., 1995; Gonzalez et al., 1998; Ratte, 1999; Garcia-Rico et al., 2003) and ultimately into human fish-consuming communities (Williams et al., 1999; Gray et al., 2003); and (iii) the potential reduction in biodiversity and abundance of marine communities, due either directly to smothering or contaminating benthic communities (Castilla and Nealler, 1978; Olsgard and Hasle, 1993; Castilla, 1996; Kline, 1999; Kline and Sketoll, 2001; Ellis, 2003) or indirectly to loss of habitat (Johnson et al., 1998).

Studies of the impacts of mine waste on marine ecosystems have largely focussed on the communities that are likely to be directly affected. These are usually benthic

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invertebrates in the path of the waste disposal (Anderson and Mackas, 1986; Burd et al., 2000; Odhiambo et al., 1996). There are only a few studies of the impacts on communities indirectly affected (such as fish, plankton and other bentho-pelagic or pelagic species) (e.g. Powell and Powell, 2001) These studies have focused on either a single indicator species or group (Johnson et al., 1998; Barry et al., 2000; Flynn et al., in press), or on reporting concentrations of trace metals in body tissues (Steimle et al., 1990; Buell, 1991; Ballschmiter et al., 1997; Suner et al., 1999; Williams et al., 1999; Mol et al., 2001; Powell and Powell, 2001; Scroggins et al., 2001). Consequently, we know very little about the impacts of mine waste disposal on the distribution and abundance of the less sessile marine communities such as resident fish, even though this group is the most likely to be eaten by humans. There are only a few studies of the impact of mine waste disposal on fish communities (e.g. Swales et al., 1998), especially in tropical regions, and no such studies on deepwater fish communities.

The Lihir gold mine is one of several current and proposed mining operations in the Indo-west Pacific region that may impact the marine environment. These include the Minahasa Raya (gold) and Batu Hijau (gold and copper) mines in Indonesia; the Misima gold mine in Papua New Guinea; the Atlas copper mine in the Philippines; and proposed gold, nickel, cobalt and copper mines in Papua New Guinea, Indonesia and the Philippines (e.g. PNG Resources, 2005a,b,c). The findings of the present study may have significant implications for these operations.

The Lihir gold mine disposes of two types of waste: (i) 35 million t yr^{-1} of overburden from the open cut operation, dumped by barges into deep ravines close to shore and (ii) 100,000 mega L yr^{-1} of tailings slurry from the gold processing plant that is discharged onto the steep sloping sea floor by way of a pipeline at 128 m depth. This slurry, which contains zinc, copper, arsenic, cadmium, mercury, lead, nickel, chromium and silver, is treated before disposal to reduce its toxicity and de-aerated to minimise its suspension in the water column.

Little is known about the marine communities of these coastal deepwater (50–2000 m) tropical environments. Deepwater fish, mainly from the families Lutjanidae, Serranidae and Carangidae, are found on the steep slopes and banks between 100 and 400 m depth (Crossland and Grandperrin, 1980; Ralston, 1980; Sundberg and Richards, 1984; Polovina and Ralston, 1986; Ralston et al., 1986; Ralston, 1988; Haight et al., 1993; Fry et al., 2006). These fishes are generally slow growing and long lived, have low natural mortality and mature at a late age; consequently they would be unlikely to sustain heavy mortalities from non-natural sources (Manooch, 1987; Haight et al., 1993; Fry et al., 2006).

The present study aims to assess the impacts of the Lihir gold mine waste disposal on tropical deepwater fish communities by comparing (i) fish abundances and (ii) concentrations of trace metals in the tissues of fish from regions adjacent to and away from the Lihir gold mine. It is the first comprehensive study of the impact of mine waste disposal on marine fish communities. The research was part of a larger study that also described impacts on shallow-water reef fish and the fishing communities living on the Lihir Islands group (e.g. Fry et al., 2006).

2. Methods

2.1. Description of the study area

The Lihir Islands group is in Papua New Guinea's New Ireland Province, about 900 km northeast of Port Moresby. It consists of four islands: Niolam, Mali, Masahet and Mahur (Fig. 1). The main island (Niolam) is a volcanic sea mountain emerging from greater than 2000 m depth. It consists of five miocene-pleistocene volcanic units, of which three are volcanic calderas and two are sequences of mafic volcanic rock that predate the three volcanoes. These volcanos contain an abundance of hydrothermal breccias that are characterised by elevated levels of As, Cu, Mo and Pb (Müller et al., 2002). Remnant geothermal activity is present in the Luise caldera, evidenced by hot springs and fumeroles. The surrounding reef-edge is narrow and grades steeply into deep water.

The Lihir Islands group is less than 300 km from the equator. The main natural physical influences on the marine environment are the prevailing ocean currents, which are tropical in origin and flow mostly from south to north. The New Guinea Coastal Undercurrent, which originates in the northeast Coral Sea, has the strongest influence (Burrage, 1993). The sea temperature remains relatively constant (25–32 °C) throughout the year and the winds are monsoonal, from the northwest for most of the year. The Lihir gold mine is close to the shores of Luise Harbour on the central east coast of Niolam Island (Fig. 2).

2.2. Sample design

The difficulty in sampling fish in deepwater environments has restricted this study to the species that take baits on hook and line fishing gear. Three separate sample designs were used: two stratified by proximity to the mine and another based on distance from the mine (described below). The designs were different to minimise the risk of a single design proving sub-optimal because deciding which regions were likely to be mine affected and which unaffected was necessarily arbitrary. In order to facilitate these designs, the islands of Niolam, Mali, Masahet and Mahur were divided into 17 locations around their perimeter and groups of these locations (called regions for convenience) were used to differentiate two of the three sample designs (see Fig. 2a). The deepwater fishing stations were also sampled at four depth strata – 20–50 m, 50–120 m, 120–200 m and 200–350 m – to ensure coverage of these habitats.

The aim of the sampling program was to obtain a similar data collection effort from each of the regions in the first two designs described below:

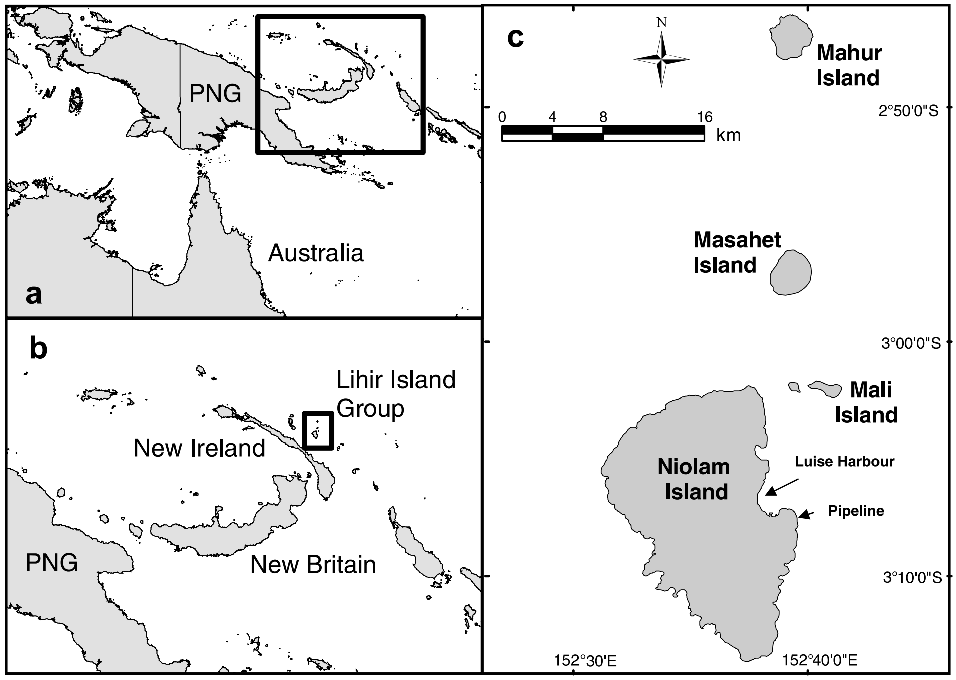

Fig. 1. The Lihir Islands group showing their position off the coast of New Ireland and Papua New Guinea. Luise Harbour, the site of dumping of mine overburden, and the position of the pipeline which deposits waste slurry from the processing plant are also shown.

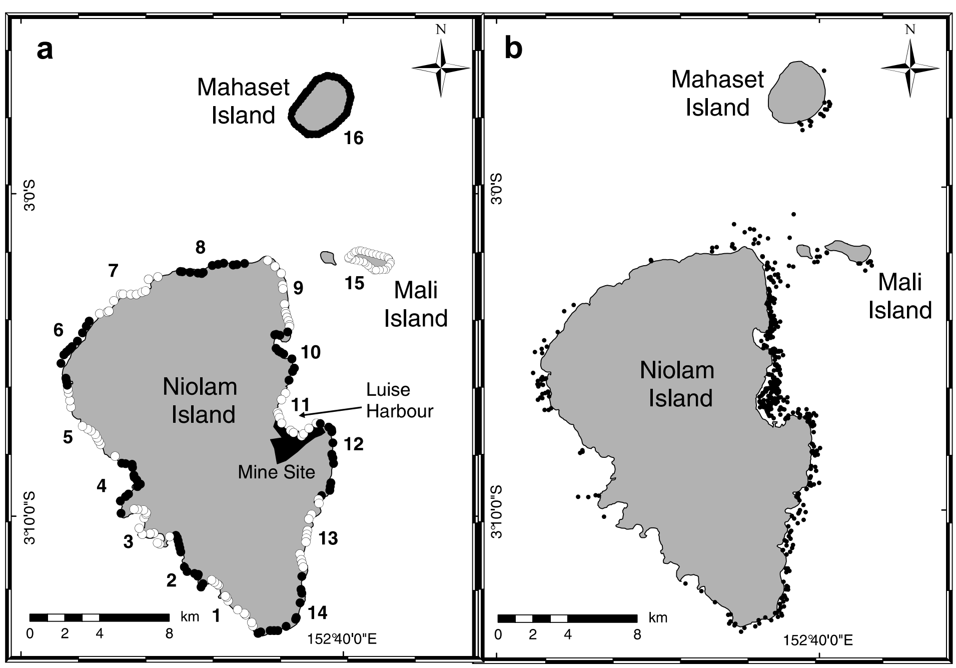

Fig. 2. (a) The Lihir Islands group showing 16 of the 17 sampling locations (shown by alternating black and white circles) used as the basis for the determining the sampling regions used to compare fish catches. (b) Niolam Island showing the sampling stations, the location of Luise Harbour and the mine site. Mahur Island not shown.

1. Proximity design: This design uses four different regions based on their proximity to the mine: (a) the mine (location 11); (b) north of the mine (locations 9 and 10); (c) south of the mine (locations 12 and 13); and (d) away from the mine (all other locations).
2. Sediment plume design: This design uses three different regions based on the known dispersal of the sediment plume (Lihir Management Company Pty Limited, 1996) generated by the mines waste disposal: (a) the mine (location 11); (b) the intermediate mine-affected

area (half of location 12 to the south of the mine; and three to the north, locations 8–10); and (c) away from the mine (all other locations).

3. Adjusted distance design: This is based on the measured distance from the mine site in Luise Harbour to each individual sampling site. The distances to sampling sites to the south of the mine (locations 12–14) were then adjusted by halving the distance to account for the influence of the south to north current flow.

2.3. Field sampling

Data were collected in the summer months for the three years between 1999 and 2002 (November 1999, November 2000 and February 2002). Each sampling trip took between two and four weeks to complete and the sampling days were randomised between the different regions, depending on the weather. In each yearly sample we aimed to complete a minimum of 30 stations from each region. Field sampling for the first year was conducted over three separate time periods: 12–29 November 1999, 9–15 February 2000 and 14–21 March 2000; in the second year over two time periods: 23 November–5 December 2000 and 8–13 March 2001; and in the third year from the 19 January to the 11 February 2002.

Samples were collected by dropline fishing from a 9 m aluminium vessel, a 5.5 m aluminium monohull vessel, or a 6 m fibreglass open dinghy (usually used for the shallower depths). After assessing the wind and current direction, each vessel was positioned on a station in the chosen depth zone and allowed to drift fish until it moved out of the depth range. The vessel was then repositioned and fishing continued. In windy conditions, vessels used a grapple anchor to remain on station. The fishing duration at each station was usually between 20 and 30 min (although sometimes up to 2 or 3 h). Fishing time was recorded as actual bottom time; when the gear reached the sea floor to when the gear was lifted off the sea floor for retrieval. The fishing lines were left down until bites were felt on the line or after about 10 min without any bites. They were then lifted and checked for fish, baits were replaced if needed and the lines dropped again. At the end of the fishing period, the end position, time and depth were again recorded. Once all the four depth zones at a site were completed, the vessels would then move to the next site and repeat the sampling procedure.

The fish were caught with three manual 'Alvey' 45 cm dropline reels spooled with 60 or 100 lb fishing line. The standard rig used was three 'size 13/0 Mustard Tuna Circle' hooks attached at intervals of about 60 cm from the main line. A 0.5–1.0 kg lead weight was attached to the end of the main line. The bait was usually either skipjack or bigeye tuna. On the smallest boat, fishing was carried out using three plastic hand reels rigged with 20 lb line and a single 'size 1 long shank' hook positioned 30 cm above a small lead weight and baited with tuna. For each fish caught, the station number and reel number were recorded on catch sheets and the fish placed into a cool box containing crushed ice.

All teleost fish caught from the dropline survey were identified to species on site by project scientists, using a range of taxonomic keys, and where necessary, returned to the laboratory for validation. Fish were also measured by standard length (SL in mm) and weighed (to nearest ±10 g) on the same day of capture. Muscle and liver tissues (1–2 g) were removed with stainless steel scalpels and forceps, washed in distilled water, then stored in polyethelene bags and frozen for trace metal analysis.

2.4. Trace metal tissue analyses

Trace metal concentrations in fish tissues were compared with individuals caught at different distances from the mine or in different regions depending on which sample design was used. They were also compared with tissues collected during a baseline study in 1994, three years before the start of the mine in 1997. Fish tissues, kept from the baseline study, came from a variety of species and were processed in the same manner as in the current study, described below.

In the laboratory, the fish muscle samples were thawed, then homogenised with a laboratory blender, sub-sampled (if required) and digested by adding 5 mL of nitric acid, to a weighed sample (±0.1 g) and allowing the mixture to stand for 18 h. The samples were then heated by microwave at 20% power for 15 min and 10% power for another 15 min. After cooling, 1 mL of hydrogen peroxide was added and the samples heated in the microwave for another 10 min at 10% power. Finally, the sample was diluted to a total volume of 100 mL with milli-Q water. The fish liver samples were treated in a similar manner, except that 15 mL of nitric acid was added and the samples were heated on a hotplate instead of the microwave to remove the top layer of dissolved fats.

The sample fish tissue and liver solutions were analysed by inductively coupled plasma mass spectrometry (ICPMS) (Ag, As, Cd, Co, Cu, Ni, Pb, Zn); inductively coupled plasma atomic emission spectrometry (ICP-AES)(Al) and cold vapour atomic fluorescence spectrometry (CV-AFS)(Hg). The detection limits of the ICPMS for each element analysed was Ag: 0.01 mg kg^{-1}; As: 0.1 mg kg^{-1}; Cd and Co: 0.01 mg kg^{-1}; Cu, Ni, Pb and Zn: 0.1 mg kg^{-1}. For Al, which was analysed by ICPMS–AES, the detection limit was 2 mg kg^{-1}; for Hg, analysed by CV-AFS, the limit was 0.005 mg kg^{-1}.

During analysis of the fish tissue solutions, samples were interspersed with check standard solutions, standard and digest blanks (usually 1 in 10 samples); standard reference biota samples (1 in 20 samples); spiked sample solutions (1 in 20 samples) and repeat digestions of samples (1 in 20 samples).

2.5. Data analyses

The impacts of the mine on the abundances of fish at 20–350 m deep were assessed by comparing (i) the probability of catching a fish between regions and distances from the mine, (ii) catch rates of total fish numbers between regions and distances from the mine, and (iii) catch rates of individual species between regions and distances from the mine. As the probability of capture and fish abundances were not normally distributed, they were analysed with different error structures. Probability of capture was examined with logistic regression that assumes a binomial error distribution. The mean catch rates of each species were examined by a log-linear model with a Poisson error distribution. All analyses were done using S-PLUS (Insightful Corporation, Seattle, Washington).

The model compared the expected probability of capture $E(p)$ or expected catch rates $E(r)$ where generically we put $E(\text{measure}) = \mu$. These expected values were compared between regions (R_i) after accounting for other effects. The model standardised the comparisons to account for variability due to secondary factors (year Y_j, depth d, number of fishing reels r and fishing duration fd):

$$\log \mu = R_i + Y_j + s(d) + \log(r \cdot fd), \quad (1)$$

where $s(d)$ is a flexible term in depth using natural splines with fixed knots. The final term, $\log(r \cdot fd)$, is a predictor in the case of a binary response and has a regression coefficient associated with it. In the case of a count response, however, this is an offset term with fixed coefficient of unity, included in the model to allow for the expectation that the mean number of fish caught should be proportional to the total fishing time. This in turn implies that, even if the response is formally a count of fish caught, the analysis is effectively comparing catch rates. All fish caught were included in the analyses of total fish numbers and capture probabilities. The analyses of the abundances of each fish species were restricted to those species that were caught often enough in more than one region (~20 or more) and the distribution of their catch rates would allow a robust and meaningful statistical comparison between regions.

Comparisons of trace metal concentrations between fish tissues from different regions or time periods (baseline vs present study) were made by *t*-tests. The effect of the mine was examined by correlating fish tissue concentrations of each species with distance from the mine outfall. The effect of fish length and weight on tissue concentrations were removed before analysis by partialling out their effects (SAS Proc Corr, SAS Institute Inc. V9.1 Box 8000 Cary, NC).

Repeat sample trace metal analyses were compared to initial analyses for all elements by *t*-tests with pooled variances. The recovery rates of each element were examined for deviation from 100% by one-sample *t*-tests; reference samples of certified tissues were compared to the certified concentrations by the same approach. As sufficient samples of many species in the different design regions could not be obtained, we present only the results for species where $n \geqslant 3$ in each treatment or the total sample size was greater than five.

3. Results

A total of 458 stations (Fig. 2b) were sampled during the three-year study. The numbers in each region varied for each sampling design, as follows:

1. Proximity design: Mine location – 110 stns; north of the mine – 149 stns; south of the mine – 79 stns; away from the mine – 120 stns.
2. Sediment plume design: Mine location – 110 stns; intermediate mine-affected locations – 203 stns; away from the mine – 145 stns.
3. Adjusted distance design: Used all 458 stations in a continuum of distances from the mine location.

3.1. Differences in fish abundances

A total of 975 fish of 98 species were caught. Of these, 17 species made up 61% of the total catch: ten lutjanid, four serranid, two carangid and one lethrinid species. Total fish numbers caught were significantly lower at the mine than in the regions, or distances, away from the mine, from all three sample designs analysed (Fig. 3, Table 1, $P < 0.001$). The probability of catching a fish was also significantly lower in the mine region for both the Proximity design (mine: 0.52 ± 0.56; north: 0.78 ± 0.04; south: 0.78 ± 0.04; away: 0.79 ± 0.04; $P < 0.001$) and the sediment plume design (mine: 0.52 ± 0.06; mine-affected: 0.74 ± 0.04; away: 0.84 ± 0.03; $P < 0.001$). There was also a highly significant change ($P < 0.001$) in the probability of catching a fish based on the adjusted distance of the catch site from the mine (Table 1), with the lowest probability adjacent to the mine and highest away from the mine.

Of the 17 species analysed, 15 had significantly different abundances between regions; 13 using the Sediment plume design, 14 using the proximity design and 13 using the adjusted distance design. Only the serranids, *Cephalopholis sexmaculata* (six-blotch hind) and *Variola albimarginata* (white-edged lyretail), showed no difference in catch rates between regions in all three sampling designs. Both the sediment plume and adjusted distance design also found no difference in catch rates between regions for *Lethrinus erythracanthus* (orange-spotted emperor) and *Lutjanus boutton* (Moluccan snapper), whereas the proximity design found no difference in catch rates between regions for *Etelis carbunclulus* (Ruby snapper). The detailed results of differences between regions are described (below) for both the sediment plume and adjusted distance designs.

Of the 15 species with significantly different abundances between regions, seven were caught in lowest numbers near the mine and highest in regions away from the mine (Fig. 3,

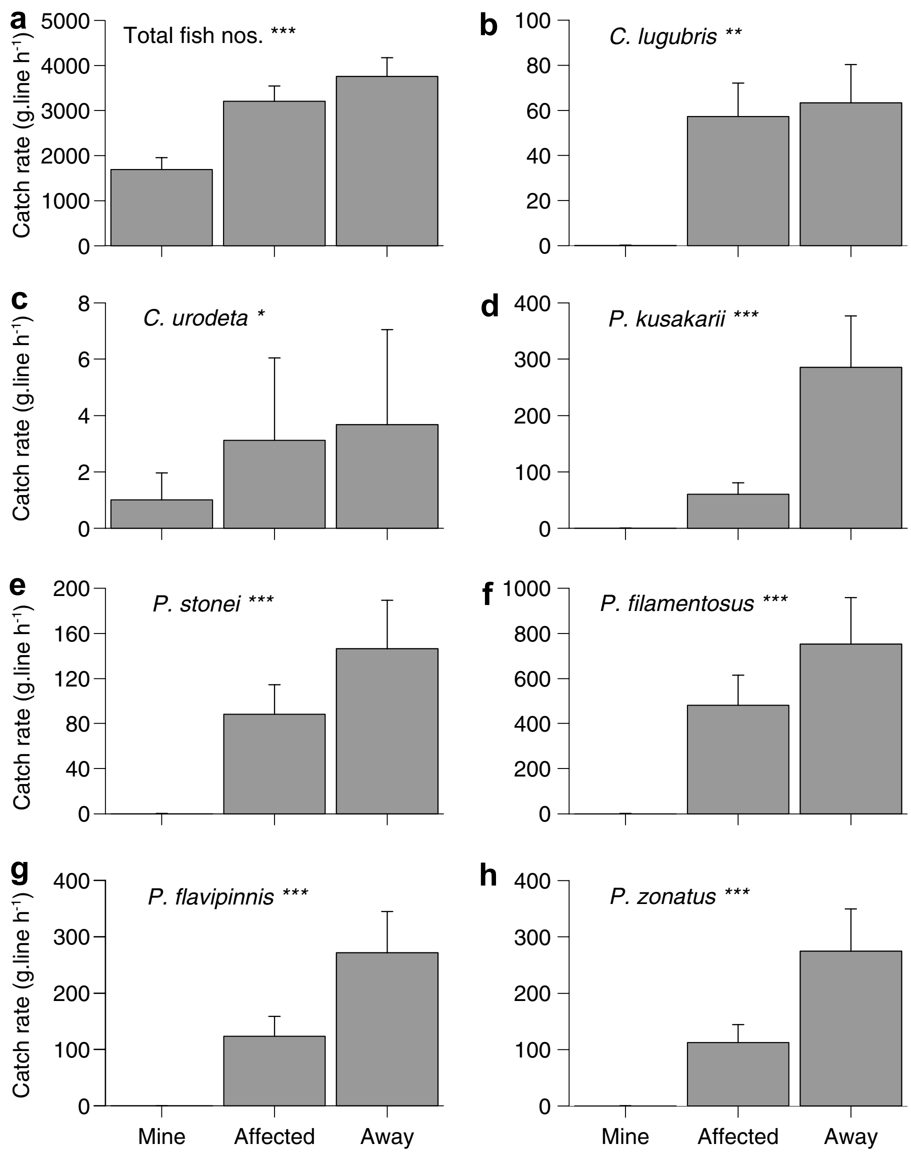

Fig. 3. The mean catch rates and standard errors for fish with the lowest abundances in the mine region, highest abundances away from the mine and analysed using the sediment plume sample design; including (a) all fish combined and (b)–(h) eight individual species. Significance levels are indicated as ***($P < 0.001$), **($P < 0.01$) or *($P < 0.05$).

Table 1). Three species – *Caranx tille* (Tille trevally), *Lutjanus argentimaculatus* (Mangrove red snapper) and *L. timorensis* (Timor snapper) – had highest abundances in the mine region (Fig. 4). Two of the species with lowest catch rates at sites adjacent to the mine – *Epinephelus morrhua* (Comet grouper) and *Pristipomoides multidens* (Goldband snapper) – had highest catch rates in the intermediate mine-affected area. One species – *Etelis carbunculus* – had highest catch rates in the intermediate area and lowest catch rates away from the mine (Fig. 4).

3.2. Trace metal tissue analyses

The fish tissue analyses were highly repeatable and there were no significant differences for any element between repeat analyses of the same sample ($P > 0.5$). The means of each series of analyses differed by less than 25% for all elements. Nickel and Cd were the least repeatable elements in muscle tissue. Cadmium was present in low concentrations, and below the detection limit of the ICPMS ($0.01\ \mathrm{mg\ kg^{-1}}$) for some samples. Spike recoveries were excellent and ranged between 92% and 101% for both liver and muscle tissue samples. Mean certified reference material recoveries generally ranged between 85% to 110% of the certified value. This range is regarded as acceptable in most analytical laboratories. The exceptions were: (i) certified liver tissue: Ag (80% mean recovery [m.r.]), Co (77% m.r.), Ni (130% m.r.); and (ii) certified muscle tissue: Al (62% m.r.), Co (70% m.r.), Ni (75% m.r.).

Overall, the quality control analyses showed that measured concentrations for As, Cd, Cu, Hg, Pb, Zn and Al (liver tissue only) were both precise and accurate. We found reduced recoveries of Ag, Al, Co and Ni in certified reference material samples (CSIRO and Lihir Gold Limited, unpublished data). This suggests that the concentrations of these metals may be underestimated by 20–30% in the fish tissue samples analysed. This is not likely to be a major concern, as Ag, Cd, Ni concentrations were very low in fish muscle and in most samples were below the detection limits.

3.3. Spatial pattern of trace metals in fish

The overall level of trace metal contamination of individual fish species showed little variation between regions in all cases ($P > 0.5$). This may be partly due to the small sample sizes (<10 tissues samples per species per region) and consequent low statistical power to detect an effect. However, the analysis of all fish combined showed levels of As (but no other metals) were higher in fish tissues from the away (13.0 ± 1.7) than the mine region (5.1 ± 0.9, $P < 0.05$).

Unlike the comparison of trace metal concentrations between regions, more metals correlated with the distance from the mine outfall (Table 2). For individual species, most of the statistically significant correlations were negative (lower concentrations further away from the mine), with the exceptions of Pb in *Cephalopholis urodeta* (Flag-tailed rockcod) and Cd in *L. boutton*. Arsenic concentrations in fish muscle were significantly negatively correlated with distance from the mine in two species and Hg in three. One species – *C. urodeta* – had a negative correlation for both As and Hg in muscle tissue (Table 2). When all fish were combined, the concentration of As and Hg was positively correlated with the distance from the mine (Table 2; $P < 0.01$). However, there was no correlation between any trace metal concentration and distance from the mine for 7 of 13 species analysed during the current study, and for all species studied during the baseline study.

3.4. Temporal changes in trace metal concentrations

The overall level of trace metal contamination was similar in both studies: 238 of 320 fish (74%) collected during the baseline and 127 of 164 fish (77%) in the current study had at least one trace metal above the recommended Australian Food Standard (AFS) limit (Table 3a). The mean concentration of trace metals in the muscle and liver of 56 species was examined. Only nine were caught in both studies and five had been sampled sufficiently to be comparable ($n > 5$) (Tables 3a and 3b).

Arsenic was the only trace metal that was consistently found in concentrations above the AFS recommended limit ($2\ \mathrm{mg\ kg^{-1}}$) in most of the samples of any species (Table 3a). The majority of samples from four of the five species analysed had elevated As concentrations. *Balistapus undulatus* (orange-lined triggerfish) had the highest concentration of As of any species sampled in either the baseline or current study. Mercury was the only other trace metal from either study with concentrations above the AFS recommended limit ($0.5\ \mathrm{mg\ kg^{-1}}$) (Table 3a).

About half of the trace metals were measured in higher concentrations in muscle and liver tissue from the baseline study when all fish were combined (Tables 3a and 3b). This was also the case for the most abundantly sampled fish, *B. undulatus*. There were few differences in trace metal

Table 1
Results from a correlation of deepwater fish catch rates with their adjusted distance from the mine, for all fish combined and 17 deepwater species

Fish category	Number of fish	Number of stations	Distance from the mine – correlation and significance
Probability of catching a fish	975	258	+ (***)
Total fish numbers	975	258	+ (***)
Caranx lugubris	32	21	+ (***)
C. tille	17	6	− (***)
Cephalopholis sexmaculata	18	15	ns
Cephalopholis urodeta	33	19	+ (*)
Epinephalus morhua	27	18	+ (**)
Etelis carbunculus	84	28	+ (***)
Lethrinus erythracanthus	21	19	ns
Lutjanus argentimaculatus	7	6	− (***)
L. boutton	23	19	ns
L. timorensis	27	20	− (***)
Paracaesio kusakarii	66	19	+ (***)
P. stonei	49	25	+ (***)
Pristipomoides filamentosus	56	28	+ (***)
P. flavipinnis	40	20	+ (***)
P. multidens	54	27	+ (***)
P. zonatus	54	32	+ (***)
Variola albimarginata	19	15	ns

Direction of correlation is either positive (+) or negative (−); statistically significant differences in catch rates are indicated by * ($P < 0.05$), ** ($P < 0.01$) and *** ($P < 0.001$). The number of fish caught in the study and the number of sampling stations from which each was caught is also presented. ns = not significant.

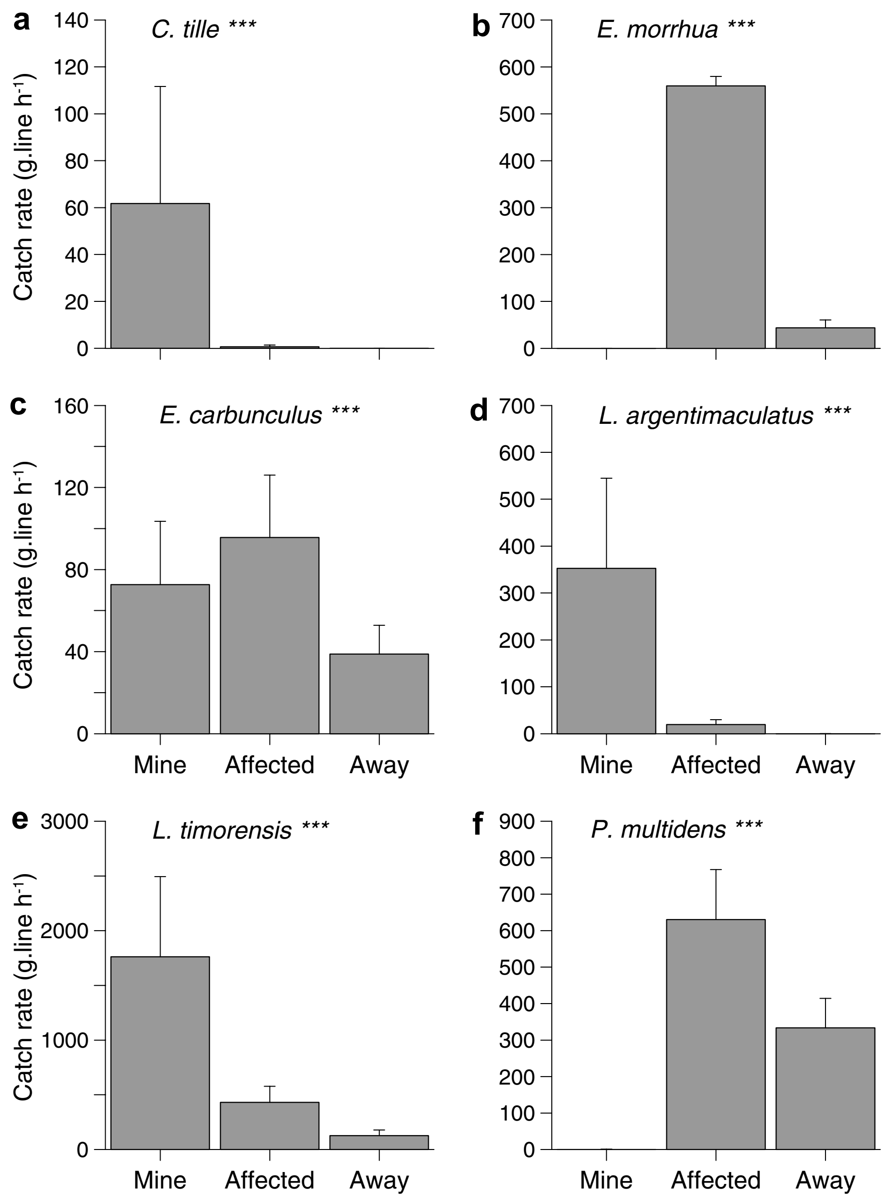

Fig. 4. The mean catch rates and standard errors for fish species with the highest abundances in either the mine or intermediate-affected region and analysed using the sediment plume sample design. Significance levels are indicated as ***($P < 0.001$).

concentrations for most of the muscle tissue comparisons within individual species. However, zinc was in higher concentrations in the current study for three of the five species, and higher in the baseline study for the other species. The only other differences were *Wattsia mossambica* having higher concentrations of Cu and Hg in the current study (Table 3a).

There were also few differences in trace metal concentrations for most of the liver tissue comparisons within individual species. However, most metals were in higher concentrations in the baseline study in liver tissues of *E. morrhua* and *P. multidens*. *W. mossambica* (Zn) and *P. multidens* (Al) were the only species to show significantly higher metal concentrations in liver in the current study (Table 3b).

4. Discussion

4.1. Differences in fish abundances

The potential impacts of the mine on the abundance of deepwater fish appear to be quite localised. The total catches of deepwater fish were lowest close to the mine waste disposal region. Similarly, around half of the species were in lowest numbers close to the mine waste disposal region. In most of these cases, the mean catch rates were usually very low at the mine, while the adjacent and distant regions had catch rates several orders of magnitude higher. Some species had highest abundances in the intermediate regions to the north or south of the mine region; a possible indication that fish populations can return to their natural

Table 2
The correlation (r^2) between trace metal concentrations in of fish tissues (1999–2002 post-mine study) and their distance from the Lihir gold mine outfall

Species	*n*	As		Cd		Cu		Hg		Pb	
		Liver	Muscle	Liver	Muscle	Liver	Muscle	Liver	Muscle	Liver	Muscle
All fish	164	0.14	0.23^{**}	0.27	−0.05	0.13	−0.06	0.06	0.23^{**}	-0.16^{*}	−0.09
Balistapus undulatus	11	0.24	−0.16	−0.09	0.32	−0.08	0.30	−0.37	−0.23	–	–
Cephalopholis sexmaculata	6	−0.29	−0.31	0.06	0.21	0.14	−0.34	−0.72	-0.91^{**}	–	–
C. spiloparaea	8	0.41	0.49	0.69	0.02	0.48	−0.32	0.55	0.52	−0.24	−0.26
C. urodeta	17	0.02	-0.57^{*}	−0.17	−0.20	0.43	0.33	-0.84^{***}	-0.90^{***}	0.50^{*}	–
Cephalopholis sp.	8	0.52	0.58	0.39	0.31	0.30	0.61	0.32	0.07	–	–
Epinephalus morrhua	4	−0.56	−0.07	−0.15	–	−0.33	−0.66	−0.17	−0.05	–	–
Lethrinus erythracanthus	7	−0.45	−0.29	−0.15	−0.29	0.13	−0.32	-0.86^{**}	-0.79^{*}	−0.41	−0.20
Lipocheilus carnolabrum	3	−0.81	0.56	−0.85	−0.84	−0.62	−1.0	−0.83	−0.66	–	–
Lutjanus boutton	10	−0.04	−0.22	0.37	0.73^{**}	0.58	0.54	−0.25	0.13	−0.39	–
L. timorensis	10	-0.84^{**}	-0.82^{**}	0.05	−0.36	−0.34	−0.28	0.21	−0.33	–	–
Melichthys vidua	3	−0.92	0.86	−0.50	–	−0.50	-1.0^{*}	−0.47	−0.50	–	–
Variola albimarginata	4	−0.24	−0.26	0.91	0.16	0.06	−0.88	0.83	0.78	–	−0.88
Wattsia mossambica	9	−0.42	−0.18	−0.21	−0.46	−0.29	−0.19	0.49	0.57	−0.60	–

Statistically significant correlations are indicated by $^{*}(P < 0.05)$, $^{**}(P < 0.01)$, or $^{***}(P < 0.001)$.

levels within a short distance of the most heavily impacted area.

The reason for the lower fish numbers at the mine location is not clear, although it is likely to be a result of benthic habitat degradation and/or increases in water turbidity. These factors have been shown to significantly impact fish populations in other studies (e.g. Blaber et al., 1995; Martin et al., 1995; Johnson et al., 1998; Kingsford and Hughes, 2005). Flynn et al. (in press) also examine this issue for corals and provide the only other information on the impacts of the Lihir mine. They showed that coral (*Porites* spp.) thickness decreased with proximity to the mine as a result of heavy sedimentation loads from waste disposal.

Few other studies have demonstrated lower fish abundances in areas of mine waste disposal (Johnson et al., 1998; Swales et al., 1998; Barry et al., 2000). Only one of these (Swales et al., 1998) dealt with multiple species, although in a freshwater system. They described significant declines in fish catches and high levels of copper, zinc, lead and cadmium in fish tissues from the reaches of the Fly River closest to the Ok Tedi copper mine, which disposed of waste into the headwaters. Barry et al. (2000) showed that the abundance of *Oncorhynchus keta* (salmon) fry was lower at sites contaminated with acid mine drainage from an abandoned copper mine in British Columbia than in reference areas. Johnson et al. (1998) used laboratory studies to demonstrate how juvenile *Pleuronectes asper* (yellowfin sole) avoided sediment covered in fresh gold mine tailings in favour of natural sediments or sediment covered in old and weathered tailings.

There is also evidence from ours and other studies that the impact of the mine waste on marine organisms cannot be generalised across all species. Some fish species in the current study are more abundant in the highly turbid mine region. These species (*C. tille*, *L. argentimaculatus* and *L. timorensis*) are usually reef-associated. However, juvenile and sub-adult *L. argentimaculatus* occur in more turbid, estuarine conditions (Blaber et al., 1994; Primavera, 1997; Carpenter and Niem, 2001) and juvenile *L. timorensis* prefer muddy coastal slopes (Froese and Pauly, 2006). The current study suggests that these three species prefer the more turbid reef-associated waters (in the mine region) to the clearer reef-associated waters further from the mine. Flynn et al. (in press) found that some coral species also survived in the impacted, high-sediment region near the Lihir gold mine.

The disposal of mine waste is not the only anthropogenic impact on fish communities at the Lihir Islands group. The local people supplement their largely vegetarian diet with both shallow and deepwater fish (Foale, 1998; Brewer et al., 2004). It is possible that the combined and growing impact of both the artisanal fishing and the mine waste disposal may have a more widespread and adverse affect on these fish species in future. We need to define and better understand these combined impacts.

4.2. Trace metal tissue analyses

Almost all fish analysed showed no difference in trace metal concentrations between regions, and most fish showed no correlation between metal concentrations and distance from the mine for all or most of the trace metals examined. Most of the significant correlations were with either Hg or As, which decreased in concentration with increasing distance from the mine. These fish may have accumulated Hg or As from the water or from their prey (or both). However, more detailed examination of their diet and their trace metal concentrations would be required before any causal relationship between the concentrations and the mine could be established.

The analyses of fish tissues collected during the baseline study in 1994 and in the current study in 1999/2002 both show As in high concentrations. The overall percentage of samples with high As concentrations is similar in both studies. The concentrations of most trace metals are also

Table 3a
The mean concentration (mean ± se in mg kg^{-1}) of trace metals in muscle tissues of species collected during the pre-mine baseline survey in 1994 (baseline) and the post-mine CSIRO survey in 2000–2001 (present)

Species	*n*	Study	Trace metal concentration (mg kg^{-1})										
			Ag	Al	As	Cd	Co	Cu	Hg	Ni	Pb	Se	Zn
All fish	320	Baseline	0.03 ± 0.001***	*<2.0*	**17.46 ± 1.4*****	0.09 ± 0.07	*<0.01*	1.72 ± 0.15	0.35 ± 0.05***	0.25 ± 0.02***	*<0.01*	4.79 ± 0.38***	22.2 ± 1.97***
	164	Present	0.01 ± 0.0004	*<2.0*	**8.1 ± 0.69**	0.04 ± 0.02	*<0.01*	0.93 ± 0.55	0.16 ± 0.01	0.13 ± 0.01	*<0.01*	*<0.01*	4.89 ± 0.45
B. undulatus	30	Baseline	0.05 ± 0.002	*<2.0*	**75.1 ± 4.7*****	0.07 ± 0.01***	*0.02 ± 0.001*	4.2 ± 0.7***	0.07 ± 0.005***	0.3 ± 0.03***	0.2 ± 0.01	1.6 ± 0.1***	88.9 ± 8.3***
	12	Present	*0.01*	2.5 ± 0.5	**26.8 ± 2.9**	0.01 ± 0.001	0.01 ± 0.001	0.5 ± 0.2	0.02 ± 0.003	0.1 ± 0.03	*<0.01*	*<0.01*	6.0 ± 1.2
E. morrhua	3	Baseline	*0.01*	*<2.0*	**7.5 ± 2.4**	*<0.01*	*<0.01*	*<0.1*	0.3 ± 0.06	0.5 ± 0.4	*<0.01*	*<0.01*	1.5 ± 0.2
	4	Present	0.02 ± 0.003	*<2.0*	**12.8 ± 3.1**	*<0.01*	*<0.01*	0.2 ± 0.02	0.4 ± 0.09	*<0.1*	*<0.01*	*<0.01*	4.3 ± 0.3***
P. filamentosus	19	Baseline	*<0.01*	*<2.0*	1.3 ± 0.1	*<0.01*	*<0.01*	0.2 ± 0.02	0.1 ± 0.02	0.1 ± 0.02	*<0.1*	*<0.01*	2.1 ± 0.2
	3	Present	0.01 ± 0.003	*<2.0*	1.4 ± 0.2	0.07 ± 0.06	*<0.01*	*<0.1*	0.08 ± 0.02	*<0.1*	*<0.1*	*<0.01*	4.3 ± 0.5***
P. multidens	21	Baseline	0.01 ± 0.002	*<2.0*	**2.0 ± 0.9**	0.01 ± 0.001	*<0.01*	0.4 ± 0.1	0.5 ± 0.2	0.2 ± 0.04	0.1 ± 0.03	1.3 ± 0.1	3.1 ± 0.6
	3	Present	*<0.01*	*<2.0*	0.8 ± 0.07	*<0.01*	*<0.01*	0.2 ± 0.03	0.1 ± 0.05	*<0.1*	*<0.1*	*<0.01*	4.4 ± 0.06*
W. mossambica	18	Baseline	*<0.01*	*<2.0*	**15.1 ± 2.3**	*<0.01*	*<0.01*	0.1 ± 0.01	0.3 ± 0.04	0.4 ± 0.2	0.1 ± 0.006	*<0.01*	2.3 ± 0.5
	9	Present	*<0.01*	*<2.0*	**23.0 ± 3.2**	0.05 ± 0.03	*<0.01*	0.3 ± 0.06***	**0.6 ± 0.1*****	*<0.1*	*<0.1*	*<0.01*	3.6 ± 0.3*
Aus. Food Stds			No value	>50	>2	>0.1	No value	>10	>0.5	No value	>0.5	No value	>200

Values for Australian Food Standards are displayed in the table and concentrations in muscle tissues above these standards are highlighted in bold. Values in italics are below the detection limit of the ICP-AES. Significant differences are indicated by $^{*}(P < 0.05)$, $^{**}(P < 0.01)$, $^{***}(P < 0.001)$ on the higher value.

Table 3b
The mean concentration (mean ± se in mg kg^{-1}) of trace metals in liver tissues of species collected during the pre-mine baseline survey in 1994 (baseline) and the post-mine CSIRO survey in 2000–2001 (present)

Species	*n*	Study	Trace metal concentration (mg kg^{-1})										
			Ag	Al	As	Cd	Co	Cu	Hg	Ni	Pb	Se	Zn
All fish	320	Baseline	0.23 ± 0.03***	*<2.0*	25.4 ± 1.66***	36.3 ± 3.1***	*<0.01*	27.5 ± 2.5***	1.12 ± 0.13*	1.1 ± 0.13***	*<0.1*	17.4 ± 1.5***	204 ± 18.6***
	164	Present	0.07 ± 0.01	*<2.0*	13.1 ± 1.6	11.9 ± 1.12	*<0.01*	16.1 ± 1.4	0.8 ± 0.08	0.28 ± 0.08	*<0.1*	*<0.01*	112.1 ± 9.3
B. undulatus	32	Baseline	0.07 ± 0.01	*<2.0*	38.3 ± 3.6	19.0 ± 5.9	0.2 ± 0.01	18.0 ± 3.1	0.4 ± 0.07	1.3 ± 0.4	0.3 ± 0.04	7.4 ± 1.2	666.9 ± 47.4***
	12	Present	*0.01*	2.5 ± 0.5	26.8 ± 2.9	0.01 ± 0.001	0.01 ± 0.001	0.5 ± 0.2	0.02 ± 0.003	0.1 ± 0.03	*<0.1*	*<0.01*	6.0 ± 1.2
E. morrhua	3	Baseline	0.2 ± 0.04***	3.0 ± 0.6	12.3 ± 6.4	9.1 ± 2.4***	0.2 ± 0.08***	35.7 ± 10.7***	1.6 ± 0.5***	0.8 ± 0.4***	0.2 ± 0.07***	*<0.01*	161.7 ± 54.7**
	4	Present	0.02 ± 0.003	*<2.0*	12.8 ± 3.1	*<0.01*	*<0.01*	0.2 ± 0.02	0.4 ± 0.09	*<0.1*	*<0.1*	*<0.01*	4.3 ± 0.3
P. filamentosus	19	Baseline	0.07 ± 0.01	2.4 ± 0.2	6.9 ± 0.5	25.0 ± 4.2	0.3 ± 0.03	16.6 ± 2.2	0.7 ± 0.2***	0.2 ± 0.04***	*<0.1*	*<0.01*	148.8 ± 16.0
	3	Present	0.05 ± 0.01	2.7 ± 0.7	6.9 ± 1.1	29.0 ± 14.1	0.4 ± 0.05	21.7 ± 6.3	0.2 ± 0.04	*<0.1*	*<0.1*	*<0.01*	106.3 ± 32.3
P. multidens	21	Baseline	0.1 ± 0.05	*<2.0*	6.4 ± 0.6***	14.6 ± 2.7***	0.3 ± 0.03***	26.6 ± 6.7*	2.0 ± 0.5***	0.2 ± 0.05	0.4 ± 0.3	19.0 ± 1.1***	80.0 ± 9.6
	3	Present	0.02 ± 0.003	2.3 ± 0.3***	2.4 ± 0.4	2.4 ± 0.8	0.1 ± 01	9.1 ± 4.0	0.2 ± 0.07	*<0.1*	*<0.1*	*<0.01*	47.7 ± 7.2
W. mossambica	18	Baseline	0.2 ± 0.2	3.1 ± 0.3	49.1 ± 6.2	19.5 ± 3.1	0.2 ± 0.01	10.5 ± 1.2	0.8 ± 0.2	0.4 ± 0.06	*<0.1*	*<0.01*	61.7 ± 4.5
	9	Present	0.03 ± 0.005	2.9 ± 0.6	73.4 ± 13.2	17.8 ± 5.3	0.2 ± 0.03	15.5 ± 1.9	0.9 ± 0.4	0.2 ± 0.02	0.1 ± 0.01	*<0.01*	85.8 ± 3.5***

Values in italics are below the detection limit of the ICP-AES. Significant differences are indicated by $^{*}(P < 0.05)$, $^{**}(P < 0.01)$, $^{***}(P < 0.001)$ on the higher value. There are no comparative food standards for liver tissue.

similar before and after the start of mining (1997). This suggests that the metals found in fish tissues are probably not due to the effect of the mine. Rather, they reflect the naturally occurring concentrations of these trace metals around the Lihir Islands group. This is supported by Müller et al. (2002) who describe elevated levels of As, Cu, Mo and Pb in hydrothermal breccias found abundantly in the volcanos of this island.

Other studies have found little or no trace metal contamination of animal tissues after the release of contaminated mine waste, including one at the nearby Bougainville copper mine in Papua New Guinea (Powell and Powell, 2001). However, some studies found that trace metal inputs into the marine environment have contaminated animal tissues. For example, elevated levels of Cu, Pb, Zn and Cd were found in tissues from riverine fishes in the vicinity of the Ok Tedi Copper mine, and decreasing concentrations with increasing distance from the mine (Swales et al., 1998). Higher mercury levels in fishes were found closer to a Suriname gold mine (Mol et al., 2001).

Although we found only limited evidence of trace metal contamination of fish due to mine waste disposal, almost 80% of all muscle tissues from the Lihir study had As concentrations above the AFS recommended limit of 2 mg kg^{-1}. The concentrations in fish tissue found in both the baseline and the current study are among the highest recorded in fish (Francesconi and Edmonds, 1993) and much higher than found in fish from nearby Bougainville Island (Powell et al., 1981). Most As in tissues of marine animals living in unpolluted systems is bound in organoarsenic compounds (Neff, 1997) and are relatively non-toxic (Hindmarsh, 2000). These organoarsenic compounds are bioaccumulated in humans, but the As is excreted rapidly. The main form that it is excreted, Arsenobetaine accounts for up to 94% of As in some fish species (Francesconi and Edmonds, 1993; Kirby and Maher, 2002); it is not toxic to mammals (Neff, 1997) Thus, few of these organoarsenic compounds are converted to toxic inorganic arsenite.

Arsenic occurs naturally in a number of forms (Gong et al., 2002), which differ in their distribution, metabolism and toxicity among animal species, including humans (Mandal and Suzuki, 2002). Predicting the toxicity and the potential acute effects of excessive As in fish tissues is complex. Although there are many recorded chronic and acute effects of As on humans, their severity will vary, depending on the source of As (Mandal and Suzuki, 2002). The effects can range from changes to skin pigment and hardening of the skin to reproductive and developmental deformities and cancers. However, a detailed study of the speciation and bioavailability of As in fish is needed to assess the threat to humans eating fish from the Lihir Islands.

Most As is taken up by fish through their diet (Francesconi and Edmonds, 1993; Neff, 1997; Kirby and Maher, 2002) and species higher in the food chain are most likely to have highest concentrations in their tissues. However, species lower in the food chain can also have higher total As concentrations in their tissues (Goessler et al., 1997; Maher et al., 1999). Marine algae have been found with greater concentrations of As than higher organisms (Francesconi and Edmonds, 1993). Because Giant clams (*Tridacna* spp.) have a symbiotic relationship with unicellular algae, they have among the highest total As concentrations in the world (Benson and Summons, 1981). *B. undulatus* was the only herbivore (or detritivore) sampled in adequate numbers for analyses in this study, and was the most heavily arsenic-contaminated species. This species is found at a range of depths, from the shallow-water reefs to more than 100 m (Allen and Swainston, 1993). These results suggest that lower food chain species groups, including plants, should also be examined to understand the broader impacts of this waste disposal and sources of fish contamination.

Mercury was the only other trace metal found in concentrations above the AFS from either the baseline or current study (in *W. mossambica* in the current study). Mercury accumulation in marine food chains is affected by several factors, particularly the assimilation efficiency of the fish and the efflux rate (Wang, 2002). Long and complex food chains appear to have more species with high levels of Hg (Wang, 2002). *W. mossambica* is piscivorous and may have accumulated these levels of Hg through food chain processes. However, the bioavailability and toxicity of Hg and other trace metals are strongly influenced by the physico-chemical properties as well as their gross concentrations in the animal (Wang, 2002).

The reported data for Ag, Co and Ni in liver tissues may underestimate the actual concentrations of these metals by up to 30%. Nevertheless, the concentrations of these metals in the samples analysed were low and did not indicate contamination. Our results show that tissue samples should be larger to ensure maximum recovery rates; the ideal size could be determined by pilot studies, preferably using several digest procedures to cover the range of trace metals of interest with the required levels of precision and accuracy.

5. Conclusion

There is evidence that the waste disposal from the Lihir Gold mine has resulted in a local depletion of deepwater fishes in the region closest to the disposal site. Conversely, the remaining regions around Niolam and other islands in the Lihir Islands group have not been significantly affected. There appears to be limited contamination in fish tissues caused by trace metals disposed as mine waste. These observed patterns of contamination, particularly by As, suggest natural sources. Given the vulnerability of these tropical deepwater species, it is recommended that their relative abundances be monitored throughout the life of the mine and the use and impacts on these fish resources by local communities be integrated into this program. The broader effects of mine waste disposal on the benthic and pelagic coastal food web remain unknown and should also be investigated. It is also recommended that mine management continues to consider ways to minimise both the extent and the magnitude of the impact (PNG Resources, 2005d) of the mine's waste disposal practices on marine habitats.

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