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The ecological effects of mining discharges on subtidal habitats dominated by macroalgae in northern Chile: population and community level studies

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Abstract

In 1996/97, a study was carried out to evaluate several variables related to the potential ecological effects of soluble copper and iron released as the result of direct dumping of mine tailing into the littoral zone of the Pacific Ocean off northern Chile. Variables studied included:

1. content of copper and iron in mining discharges;
2. distribution of Cu and Fe in seawater at study sites;
3. distribution of Cu and Fe in the seaweed *Lessonia trabeculata* and in its alginates (obtained from frond, stipe and holdfast);
4. alterations in *Lessonia* morphology; and
5. variability in the macroinvertebrate community associated with *Lessonia* holdfasts and the inter-plant subtidal community.

The variables were evaluated for different depths and distance from discharge sources, as well as for control areas far from any mining activity. It was observed that tailings from copper mining caused more ecological perturbation than those from iron mining; however, the lack of organisms very close to tailing discharges could be caused by stress produced by loading of fine sediments rather than by the presence of heavy metals. This work shows that the concentrations of heavy metals in seawater, plants, and alginates of *Lessonia* in contaminated and control sites were highly variable, decreasing with depth and distance from the contamination source. What were originally considered as control areas far from anthropogenic metal release, showed high concentration of heavy metal due to natural orogenetic processes occurring along the Chilean coast.

Introduction

In studies of the effects of mine tailings on littoral marine communities in the south-east Pacific, the general trend has been to refer almost exclusively to the comparative occurrence of heavy metals in different organisms (algae, invertebrates and fish) and sediments (Boré et al., 1989; Trucco et al., 1990; Vermeer & Castilla, 1991; Lecaros & Astorga, 1992; Ahumada, 1994; Vásquez & Guerra, 1996). However, most of these studies are difficult to compare due to the lack of methodological standardization and the lack of data for uncontaminated areas. This latter point is particularly relevant in northern Chile, where natural orogenetic processes, volcanic activity and climatic conditions may produce elevated levels of heavy metals in the environment, unrelated to mining activity (Vila & Sillitoe, 1991; Vásquez & Guerra, 1996).

Although the literature suggests that contamination by heavy metals may cause dramatic ecological impacts on coastal marine environments, these effects are rarely documented except in cases of overt contamination (Bryan & Langston, 1992). As suggested by Morrisey et al. (1996), the lack of evidence is partly due to the way in which these perturbations have been investigated. Traditionally, the effects of contaminants in marine environments have been approached in two ways:

1. ecotoxicological studies may identify the effects of contaminants under controlled laboratory conditions, and
2. field studies may show correlation between distribution of contaminants and the composition of benthic faunal assemblages which demonstrate environmental variability.

Unfortunately, the former type of study does not reproduce the range of potential environmental factors that regulate the magnitude of the effect. The latter type of study does not generally include the intermediate effects proper to an environmental gradient of perturbation distribution, and the eventual response of a population and/or communities to this gradient. Therefore, the actual impact of these contaminants in nature can differ widely from that reported under laboratory conditions. In this context, Bryan & Langston (1992) suggested that the effects of Cu and Zn on species distribution, although evident, were not as apparent as would be predicted under controlled laboratory conditions. For example, in the field, some deleterious effects on benthic organisms that could be directly attributed to specific effects of metallic contaminants are very scarce compared to those reported for equivalent laboratory assays.

Chile is a country of enormous mining potential, in which copper is the main export product accounting for over 60% of the total income. Between 18° and 30° S, mineral deposits include over 25% of the copper, 40% of the molybdenum, and 30% of the lithium world reserves. Moreover, in the same zone there are important deposits of Au, Fe, Ag, Mn, Co, Hg, Tu, Pb and Zn (Corvalán, 1985). Although there is evidence of serious environmental impact by the deposition of fine sediments resulting from Cu and Fe mining (e.g. Chañaral in northern Chile, 25 000 tons d^{-1} from 1939 to 1975), few data have been obtained on the effects of such discharges in marine communities (Castilla & Nealler, 1978; Castilla, 1983; Vásquez & Guerra, 1996). These authors reported changes in the species composition of intertidal areas affected by Cu tailings.

Between 18° and 42° S, subtidal rocky bottom environments to 35 m depth are dominated by *Lessonia trabeculata* (Villouta & Santelices, 1986; Vásquez, 1992). Holdfasts of *L. trabeculata*, like those of other brown macroalgae, are micro-habitats, which promote larval settlement, recruitment, and physical shelter against bottom currents and predators. A high diversity of macro-invertebrates and fish communities is associated with these habitats (Vásquez & Santelices, 1984; Ojeda & Santelices, 1984; Vásquez, 1993). Holdfasts of brown algae, a spatially and naturally delimited habitat, have been widely used as a biological model for the functioning of discrete communities (Vásquez & Santelices, 1984; Snider, 1985; Vásquez, 1993), and as study units to assess the effects of contamination (Smith & Simpson, 1993; Smith, 1996). In northern Chile, these environments have often been affected by tailings of Cu and Fe mining. Considering the logistical problems met when experimentally injecting (see Morrisey et al., 1996) heavy metals into exposed rocky environments, a valid method to experimentally study the effect of mine tailings in these communities is to determine the distribution of the contaminants over a gradient from a contamination focus, evaluating the effects on populations and/or communities related to their distance from the focus, assuming a dilution effect. This natural experiment may allow determination of *in situ* effects of mining tailings, without separating out possible co-variation effects from natural environmental variables such as temperature, salinity, pH, wave exposure and water movement. The method infers the existence of a gradient in the magnitude of the perturbations to which the biological communities are subjected to in the natural environment.

The present work characterizes some subtidal environments contaminated by Cu and Fe mining through the quantification of these cations in sea water and in *L. trabeculata* plants and alginates. It also evaluates the temporal and spatial effects of Cu and Fe tailings on *Lessonia* populations, and on rocky subtidal communities in northern Chile.

Material and methods

Rocky subtidal environments receiving solid and liquid tailings from copper (Michilla 22° 48′ S) and iron mining (Chapaco 28° 28′ S), were sampled seasonally between June 1996 and August 1997. Simultaneously, two localities 60 km north of Chapaco (Carrizal Bajo 28° 05′ S) and 100 km south of Michilla (Caleta Constitución 23° 25′ S) were evaluated as unexposed control areas (Figure 1). Samples of seawater and of the dominant subtidal populations and communities were taken in the study areas, and at permanent stations located along a distance gradient from the contamination source (0, 1, 2, 3 and 5 km) and a depth gradient (0, 10, 20 and 30 m) facing the mining discharges at Michilla and Chapaco. The subtidal localities correspond to rocky areas exposed to predominant SW winds, with coastal currents of northern direction and with bottom communities dominated by *L. trabeculata* (Vásquez, 1992).

Chemically, the study areas were characterized by the concentration of Cu^{2+} (Michilla) and Fe^{2-} (Chapaco) in bottom seawater obtained by SCUBA. The damps and outfalls that carry mining residues to the shore were simultaneously evaluated in all the study areas.

Heavy metals in seawater

The pre-concentration of the seawater samples was carried out according to Berndt et al. (1985). A 500 ml sample was filtered (0.45 μm millipore) at pH 4–5 (Na Acetate-acetic acid) and treated with 80 mg l^{-1} ammonium pyrrolidine-dithiocarbamate (APDTC) dissolved in 2 ml water. It was then vigorously stirred and filtered drop by drop through activated carbon. The metallic complexes adsorbed by the carbon were dried at 120 °C for 20 min. After the system had cooled, it was treated with 1ml HNO_3, heated and dried. Finally, the carbonaceous residue, with the metallic cations, was suspended in 1.5 ml 4.5M HNO_3 and centrifuged at 10 000 rpm for 15 min. Analytical readings were done with 200 μl aliquots of each sample by atomic absorption spectroscopy (Perkin Elmer 2380) using 1 000 μg ml^{-1} metallic Cu and Fe in 0.3 M HNO_3 (J.T. Baker-INSTRA-ANALYZED Reagent) as standards.

Heavy metals in alginates and plants of L. trabeculata

For each study area, the heavy metal content of samples of fronds, stipes and holdfasts were analysed. Additionally, the concentration of Cu and Fe were determined in alginate samples. Algae were oven-dried for 26 h at 65 °C, cut into small pieces with a plastic knife and ground in a porcelain mortar. Samples weighing approximately 2 g were ashed in a muffle furnace for 45 min at 700 °C. The ash was digested with 20 ml distilled water and filtered through Whatman N° 54 paper. The volume of the filtrate was adjusted to 50 ml with distilled water and stored in polyethylene flasks. Heavy metal concentrations were measured as above. Results are expressed as μg of metal per g of dried alga (algal content) and μg of metal per g of alginate (alginate content).

Population and community effects

In order to determine the effects of the mine tailings at the community and population level, the subtidal populations of *L. trabeculata*, the communities on hard substrata among *Lessonia* plants, and the invertebrate communities associated with *L. trabeculata* holdfasts, were sampled along the same spatial and temporal gradients where metal samples were obtained.

L. trabeculata plants were sampled *in situ*: 339 at Chapaco, 57 at Carrizal Bajo (Chapaco-control), 160 at Michilla and 50 at Caleta Constitución (Michilla control). The following measurements were taken for each plant: maximum length, holdfast basal diameter, numbers of stipes, and total weight. Frequency of reproductive plants was evaluated at each locality. Using these variables, size distribution, density, biomass, and distribution of reproductive plants representing the total of the sampled population were calculated.

The effects of Cu and Fe tailings on the structural changes of the communities associated with *L. trabeculata* holdfasts were evaluated in Michilla (n = 53), Caleta Constitución (100 km south of Michilla, n = 49), Chapaco (n = 61) and Carrizal Bajo (60 km north of Chapaco, n = 57). The holdfasts were removed by Scuba diving using crowbars, fixed in the field with 8% formaldehyde in seawater and taken to the laboratory for analysis. The fauna were extracted from the central cavity, identified when possible to the species level, counted, weighed and measured.

In each study area and throughout the distance gradient from the contamination source, the communities from hard bottoms amongst *L. trabeculata* plants were evaluated using transects of 50 m length parallel to the shore, at 10 m depth. The transects (Michilla n = 6, Chapaco n = 8) were sub-divided each 10 m, and the cover and/or density (2 replicates at random every 10 m) evaluated with 0.25 m^2 quadrats, with 100 interception points.

Spatial changes of the subtidal communities between *Lessonia* plants were evaluated by monitoring species richness, diversity, total density, total biomass and cover. Due to the lack of seasonal responses with mining discharges, population and community variables were grouped according to the distance and depth gradients. To estimate differences in the population and community parameters, one way ANOVA and *a posteriori* Tukey tests (Sokal & Rolf, 1981)

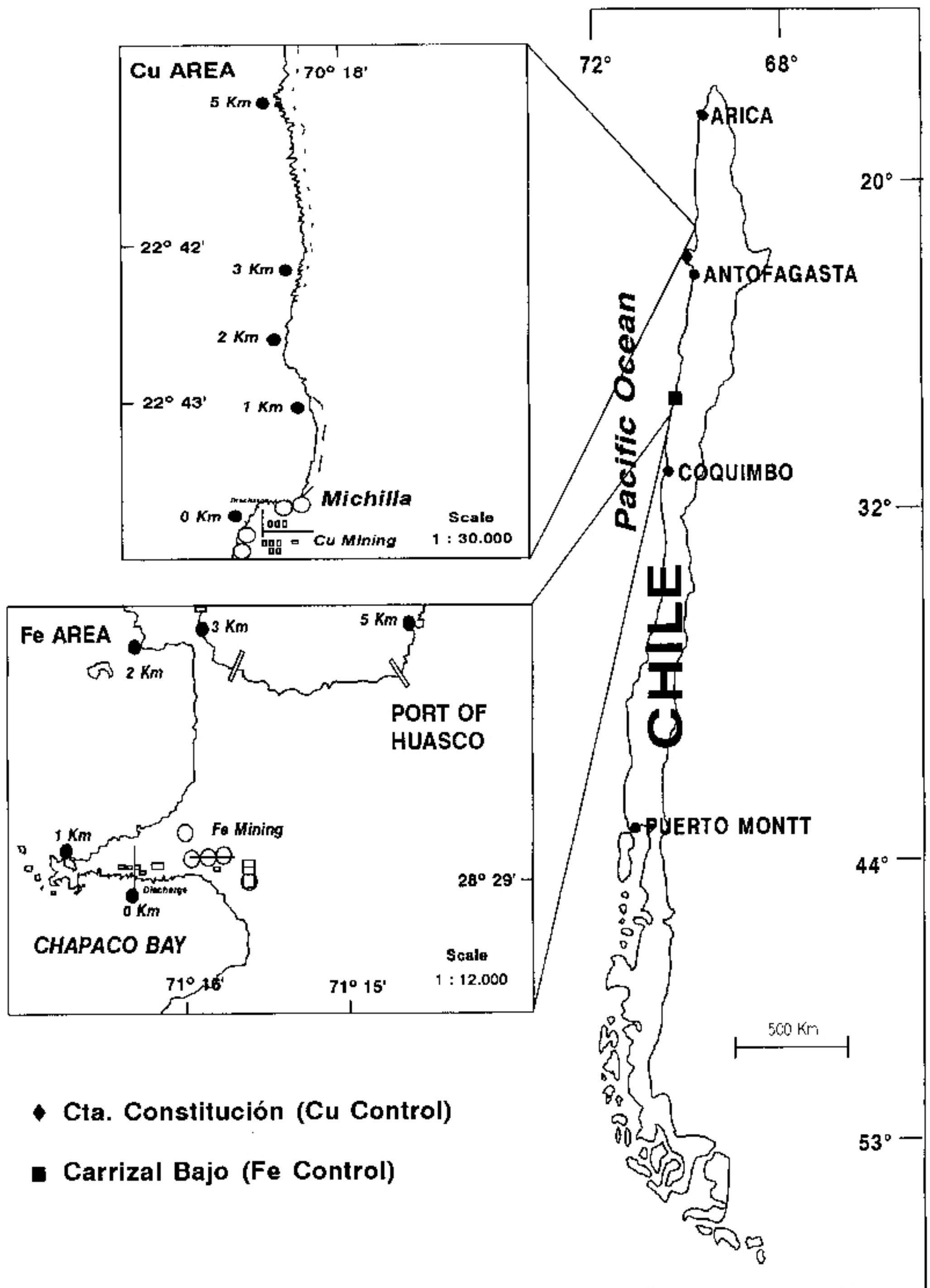

Figure 1. Location of study areas.

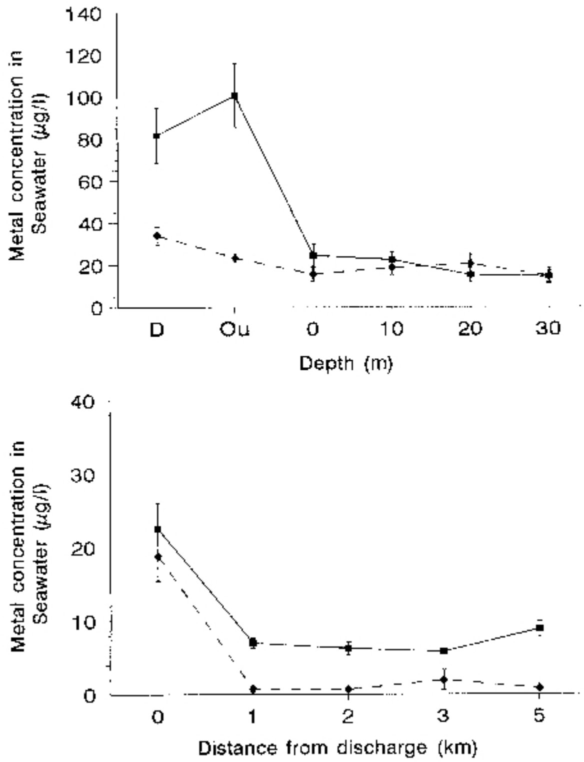

Figure 2. Variability of Cu (dashed line) and Fe (continuous line) contents in seawater along a depth (above) and distance (below) gradient from the source of mine tailings. D = dump, Ou = mining outfall. Bars = standard error.

were performed. Confidence intervals for diversity index were estimated by Jacknife (Jacksic & Medel, 1987).

Results

Heavy metals in seawater

The spatial distribution of Cu and Fe in seawater, at sites in the vicinity of mine tailings, decreased with depth (0–30 m) and with distance (0–5 km) from the contamination focus (Figure 2). At Michilla, the mean values of Cu were higher in the dam (D = 36 μg l^{-1}) and outfall (Ou = 25 μg l^{-1}) than in the intertidal areas (18 μg l^{-1}). These values did not change significantly ($p > 0.05$) until 30 m depth. Fe in seawater showed a similar pattern at Chapaco, where higher values occur in the dam and outfall (80 and 100 μg l^{-1}, respectively). These values were significantly different ($p < 0.05$) from those observed between 0 and 30 m depth, which fluctuated between 20 and 30 μg l^{-1} (Figure 2).

Between 0 and 5 km from the discharge source, Cu and Fe concentrations decreased at the two localities studied (Figure 2). Both Cu and Fe had maximum values at 0 m depth (intertidal areas), and decreased significantly ($p < 0.05$) over the first km from the contamination source. However, between 1 and 5 km from the contamination source, the values did not vary significantly ($p > 0.05$) (Figure 2).

Cu and Fe concentrations at control areas in Caleta Constitución (100 km away Michilla) and Carrizal Bajo (60 km away Chapaco) showed similar values to those of Cu at 30 m depth (23 μg l^{-1}), and were significantly higher ($p < 0.05$) than those 5 km from the contamination source. Fe concentrations (80 μg l^{-1}) in controls areas, were significantly higher ($p < 0.05$) than those observed at the limits of the depth and distance gradients at the discharge sites.

Between 0 and 30 m depth, and 0 and 5 km from the contamination source, there was no seasonal pattern of change in Cu and Fe concentrations at either Michilla or Chapaco (Figure 3). There was greater variability with depth than with distance from the mine tailings. Cu and Fe values increased in the winter months at 0 m depth and 0 km at both sites.

Heavy metals in plants and alginates

Concentrations of Cu and Fe in fronds, stipes and holdfasts of *L. trabeculata* and in alginates showed no clear pattern as a function of distance from the source of contamination (Figure 4). *Lessonia* showed variable maximum Cu concentrations in the different parts analyzed. At the control area, alginates extracted from stipes and fronds had significantly ($p < 0.05$) higher Cu values (20 μg g^{-1}) than alginates from holdfasts of the same plants (Figure 4).

At Chapaco, Fe concentrations in the different *Lessonia* structures did not vary significantly over the distance gradient studied. The high variability of metal concentrations in both the plants and extracted alginates from the study and control sites was notable (Figure 4).

Population effects

At Michilla and Chapaco, no *L. trabeculata* plants were found between 0 and 30 m depth. Within this depth range at c. 1 km from the source a fine sediment that precludes settlement and growth of algal spores and invertebrate larvae covers the rocky substratum.

The first *Lessonia* plants appeared at 3 km from Michilla, whereas a number of plants were found

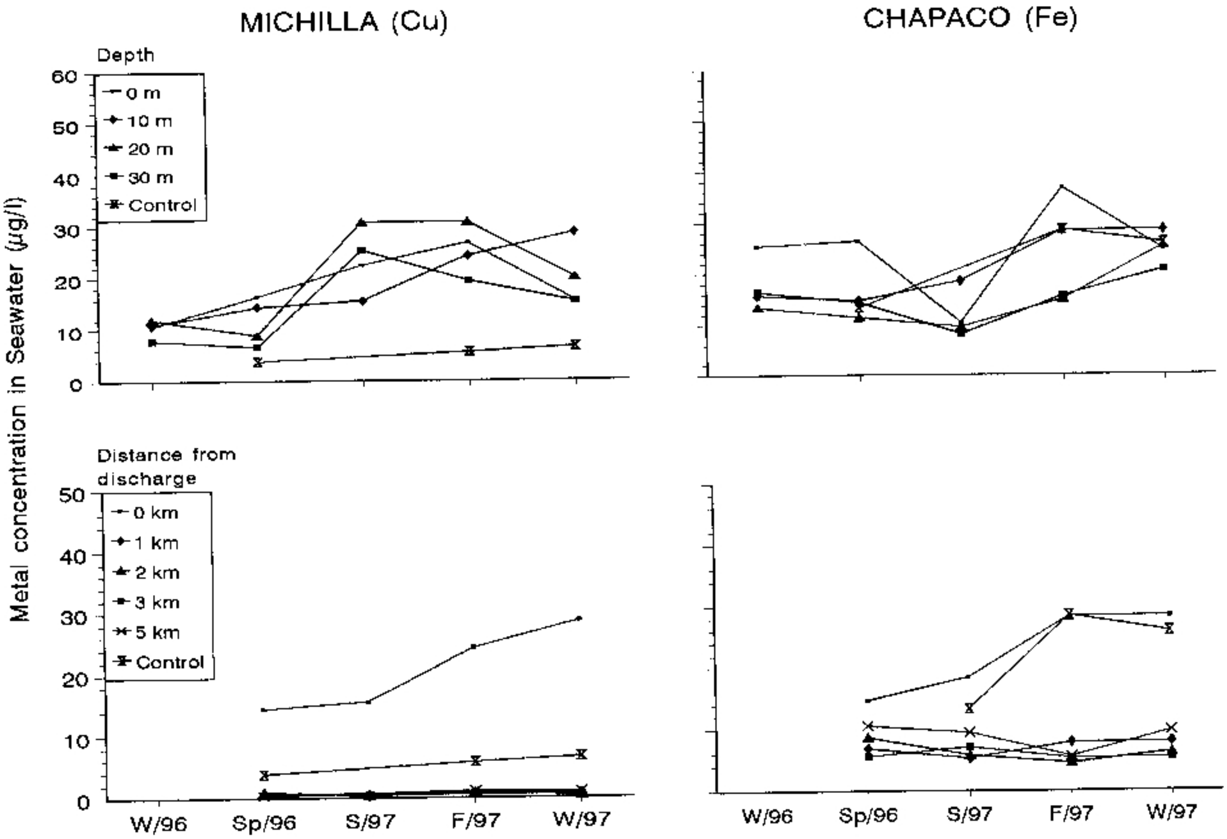

Figure 3. Seasonal variability of Cu and Fe seawater concentrations along the depth and distance gradients from the mining outfall.

only a few metres from the Fe tailing outfall at Chapaco (Figure 5). At the Michilla site, the population descriptors for *Lessonia* suggest that populations consist of individuals not exceeding 1.8 m in length and 20 cm holdfast diameter, with less than 10 stipes per plant and a mean wet weight of 5 kg. However, mean plant density is high, with over 35 plants per 10 m^2 (Figure 5).

At 5 km from Chapaco, individuals of *L. trabeculata* can exceed 2 m in length, 25 cm in mean holdfast diameter and 15 kg wet weight. The mean density increases, and the mean number of stipes per plant decreases with distance from the contamination source (Figure 5).

The higher density of juvenile plants close to the outfall of mining activities, the increase in plant size (Figure 6), and increase in the reproductive plant frequency with distance from the contamination source (Figure 7), suggest a longer survival of adult plants with decrease of the perturbation effect. Although these patterns could be produced by sediment-effect rather than heavy metal concentrations, Cu tailings produce greater perturbations than do Fe, at the population level.

Community effects

The communities of macroinvertebrates associated with *L. trabeculata* holdfasts show a significant ($p < 0.05$) reduction in number of species, density and biomass in areas closer to the Cu contamination source compared with control areas (Figure 8). Macroinvertebrate communities associated with *Lessonia* in environments contaminated by Fe tailings, show no significant differences ($p > 0.05$) with those in control areas, or with those inhabiting *Lessonia* holdfasts between 1 and 5 km from the contamination source (Figure 8). Communities on hard substrata between *Lessonia* plants showed similar responses to those observed in intra-holdfast communities at both study sites except that at 2 km from Michilla diversity on the hard bottom was high in the absence of *Lessonia* (Figure 9). Greatest effects of mining pollution were observed in areas closest to the Cu and Fe discharges.

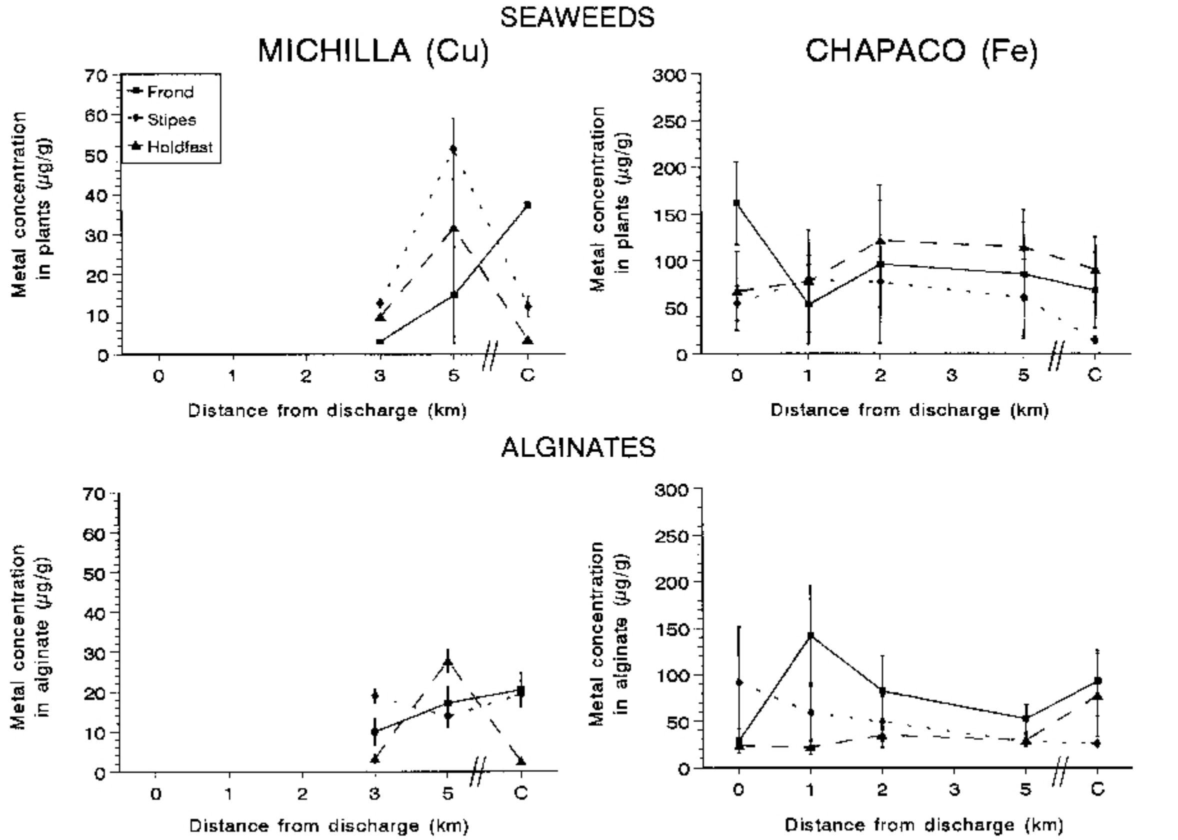

Figure 4. Content of Cu and Fe in *Lessonia trabeculata* fronds, holdfast and stipe, and alginate extracted from them, along the distance gradient. C = control area. Bars = standard error.

Discussion

This work contains the first data on the effects of mine tailings on marine subtidal populations and communities of the south-eastern Pacific. The spatial distribution of Cu and Fe in seawater, close to mine tailings, showed values that decreased with depth and with distance from the contamination source. In contrast, concentrations of Cu and Fe in fronds, stipes and holdfasts of *L. trabeculata* and in extracted alginates showed no clear pattern as a function of distance from the contamination source.

Tailings from Cu mining appear to cause more ecological perturbations than those from Fe mining. At Michilla (Cu effect) and Chapaco (Fe effect), no *L. trabeculata* plants were detected between 0 and 30 m depth. In this depth range, a fine sediment that precludes settlement and growth of benthic organisms covers the rocky substratum. The communities of macroinvertebrates associated with *Lessonia* holdfasts in the vicinity of Cu tailings show a greater reduction in species richness, density and biomass than the holdfast communities close to the Fe contamination source. Communities on hard bottoms between *Lessonia* plants showed similar responses to those observed in intra-holdfast communities at the study sites.

Even though the mining activities at Michilla between 1971 and 1994 evacuated an annual mean of 415 155 tons of solids directly to the sea, perturbations are restricted to less than 3 km distance from the contamination source. The lack of algae and other benthic organisms over the depth gradient adjacent to Cu and Fe mine tailings was probably caused by the accumulation of fine sediments rather than the heavy metal content *per se*. The 9.2×10^6 Mt of sediments dumped into the sea over 19 years at Michilla is undoubtedly the cause of the damage to the subtidal benthic communities at the study area. Castilla & Nealler (1978) have documented similar ecological damage for intertidal communities near the El Salvador copper mine in northern Chile. Resuspension of sediments during winter storms is one important

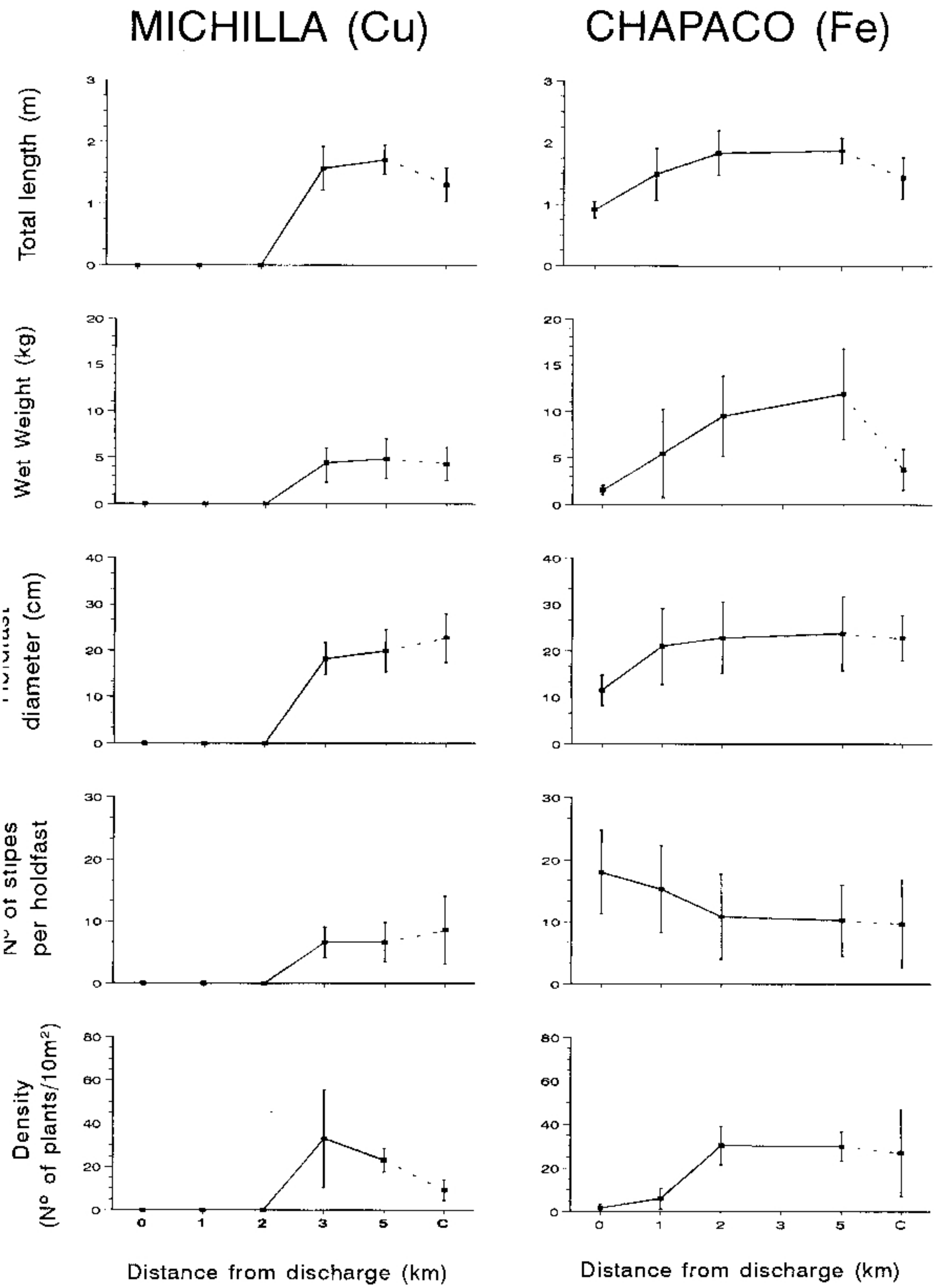

Figure 5. Spatial variability of morphological variables of *Lessonia trabeculata* populations exposed to different Cu and Fe concentrations in the field. C = control area. Bars = standard error.

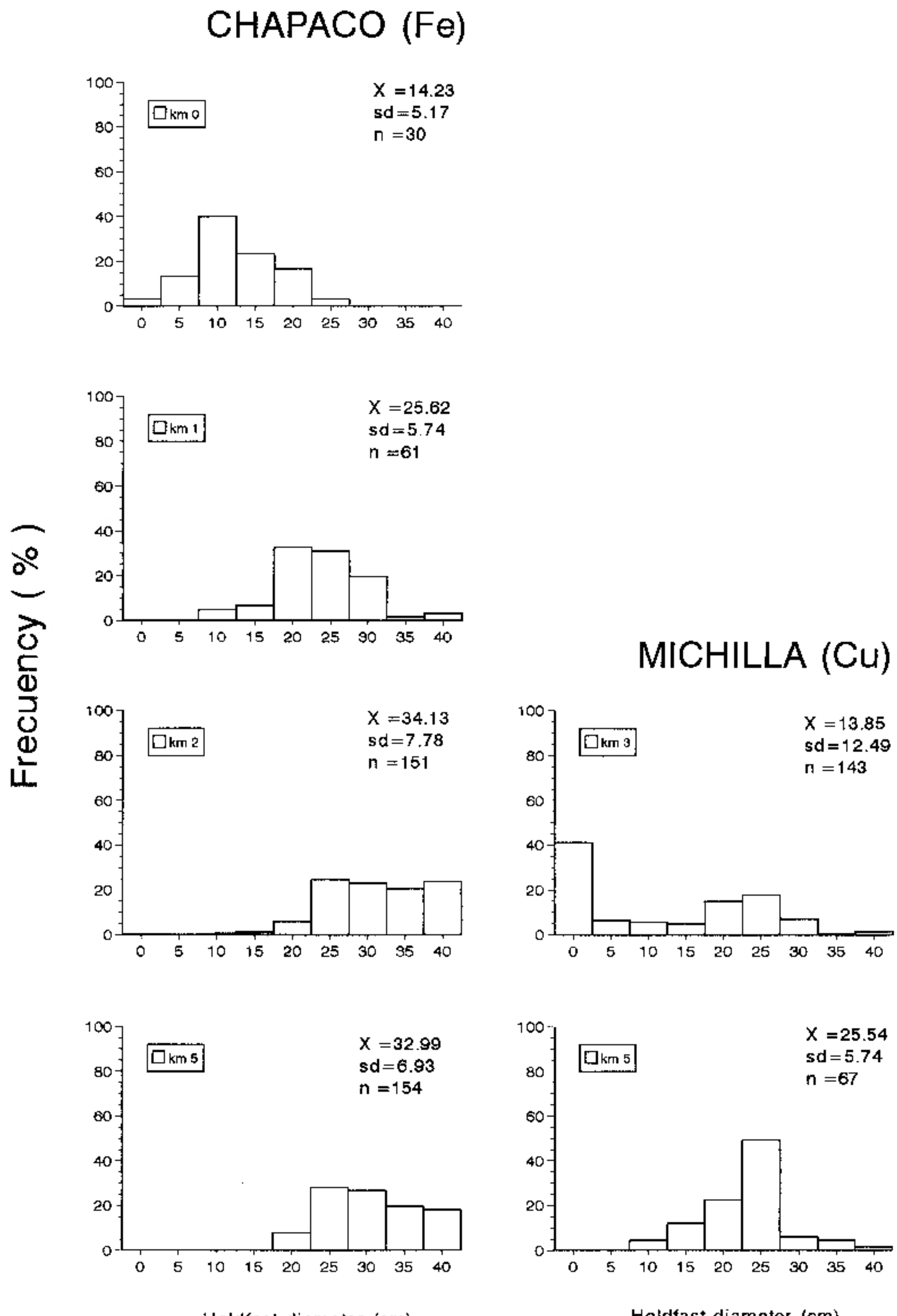

Figure 6. Spatial variability of size frequency in subtidal *Lessonia trabeculata* populations exposed to different Cu and Fe concentrations in the field.

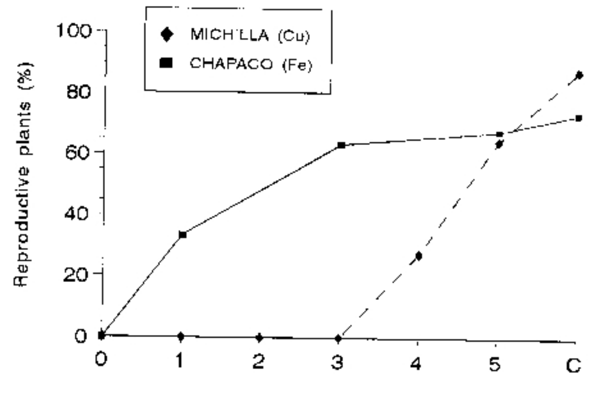

Figure 7. Frequency of reproductive plants in subtidal populations of *Lessonia trabeculata* at the study areas. C = control area. Bars = standard error.

factor that must be considered in the distribution and variability of heavy metal concentration in seawater and algae. During winter, the possibility of higher heavy metal concentration could be minimized by the greater water movement (dilution effect) caused by the predominant SW wind and surge common during this time of the year. Our data on temporal variability may reflect this phenomenon.

Tailings from Fe mining do not generate severe modifications of the subtidal populations and communities in the studied areas. Only a few meters from the tailing outfall, *Lessonia* populations have a morphology and abundance similar to those of more distant sites, and to populations in the control localities. No effects on the fauna associated with *Lessonia* holdfasts were detected in the sampling gradient. Though the concentrations of Cu and Fe exceed the 'normal' values for seawater in other latitudes (Lewis, 1994), they do not seem to generate modifications *per se*. This study shows that there are subtidal communities dominated by macroalgae (e.g. *Lessonia*) in areas with high Cu and Fe concentrations in seawater, as in the case of Carrizal Bajo (28° 05′ S), Caleta Constitución (23° 25′ S), or those reported by Vásquez & Guerra (1996) for other localities of northern Chile. The high levels of heavy metal concentration in areas without mining pollution are possibly due to orogenetic processes, high frequency of volcanic activity and climatic conditions which naturally increase its availability (Vila & Sillitoe, 1991). Other factors (not documented), which may increase the heavy metal concentrations in pristine areas of northern Chile are the runoff of summer rain from the slopes of the nearby Andes Mountains, the frequency and intensity of ENSO (El Niño Southern Oscillation), and the high degree of coastline exposure. In this context, the high levels of heavy metals all along the Chilean coast, might have resulted in adaptation in ruderal macroalgal species (*sensu* Vásquez & Guerra, 1996) allowing them to occur in coastal environments receiving high loads of anthropogenic pollution.

The sediments associated with high concentrations of heavy metals from mine tailings probably produce a greater effect than the toxic cations themselves. The kind of physical perturbations that limit the amount of light and maximize abrasion phenomena have not been assessed in the Chilean littoral, and are poorly documented for other parts of the world.

Binding of metal ions to polyphenols has been described by several authors (e.g. Ragan et al., 1979; Pedersen, 1984). Karez & Pereira (1995) found that concentrations of Zn, Cd, Pb, Cr and Cu were as much as two orders of magnitude higher in polyphenolic fractions than in whole plants of *Padina gymnospora* from south-eastern coast of Brazil coast. In general, at the most contaminated area, Cu and Pb were more concentrated in polyphenols than Zn, Cd and Cr.

Results presented here indicate that the Cu and Fe contents of extracted alginates are higher than the plants of *L. trabeculata* at the study sites. These represent the first report of heavy metal contents of alginic acid, although Paskins-Hurlburt et al. (1976) reported the metal binding properties of fucoidan.

The analysis of Cu and Fe contents in the different structures of *L. trabeculata*, particularly in alginates, shows that this macroalga is a good indicator of the heavy metal levels in seawater, although they do not disclose clear-cut variability patterns. The wide distribution range of *L. trabeculata* in subtidal communities of the south-west Pacific (Villouta & Santelices, 1986) makes this species a useful tool as study unit, not only because its individual and population characteristics may help to evaluate chemical perturbations within a distribution gradient, but also because their holdfasts contain a rich community of associated macroinvertebrates (Vásquez, 1992). These communities are discrete and biologically delimited, allowing replication over latitudinal and bathymetric gradients. Moreover, the populations occurring inside them respond differentially as a function of the perturbation to which they are exposed, and to different perturbations according to their own tolerance ranges.

This work shows that the values of heavy metals in seawater, plants and alginates of *L. trabeculata* from

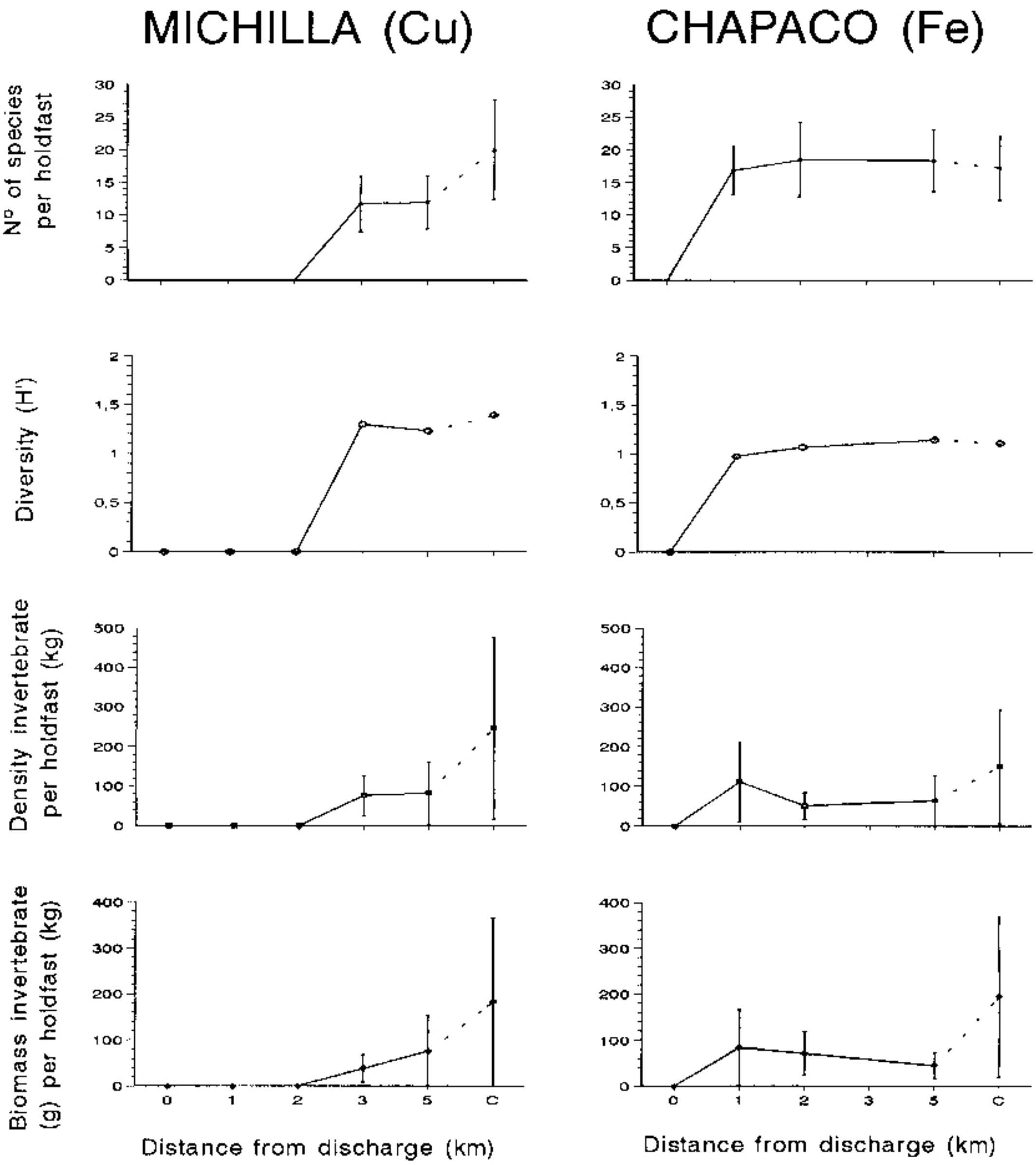

Figure 8. Spatial variability of macroinvertebrate fauna associated with *Lessonia trabeculata* holdfasts exposed to different Cu and Fe concentrations in the field. C = control area. Bars = standard error.

contaminated and control sites are highly variable. In intertidal areas adjoining the tailing ducts, the high values of Cu and Fe similar to those found in areas with the same contaminant agents in other localities of the Chilean coast (Vásquez & Guerra, 1996; Correa et al., 1996).

In laboratory experiments, exposure to the metal concentrations encountered at the study areas would result in inviability or a dramatic decrease of the reproductive and growth potentials of individuals (Bryan & Langston, 1992; Anderson & Kautsky, 1996; Gledhill et al., 1997). It is important that the influence of environmental factors such as: temperature, wind intensity, tidal regimes, water movement, wave impact, coastal circulation, local orogenetic processes, tectonic movements, shore topography, coastal upwelling and global oceanographic phenomena like ENSO, should all be considered when assessing the intensity of the effects of contaminant agents on marine coastal communities. Future field studies should assess the effects of

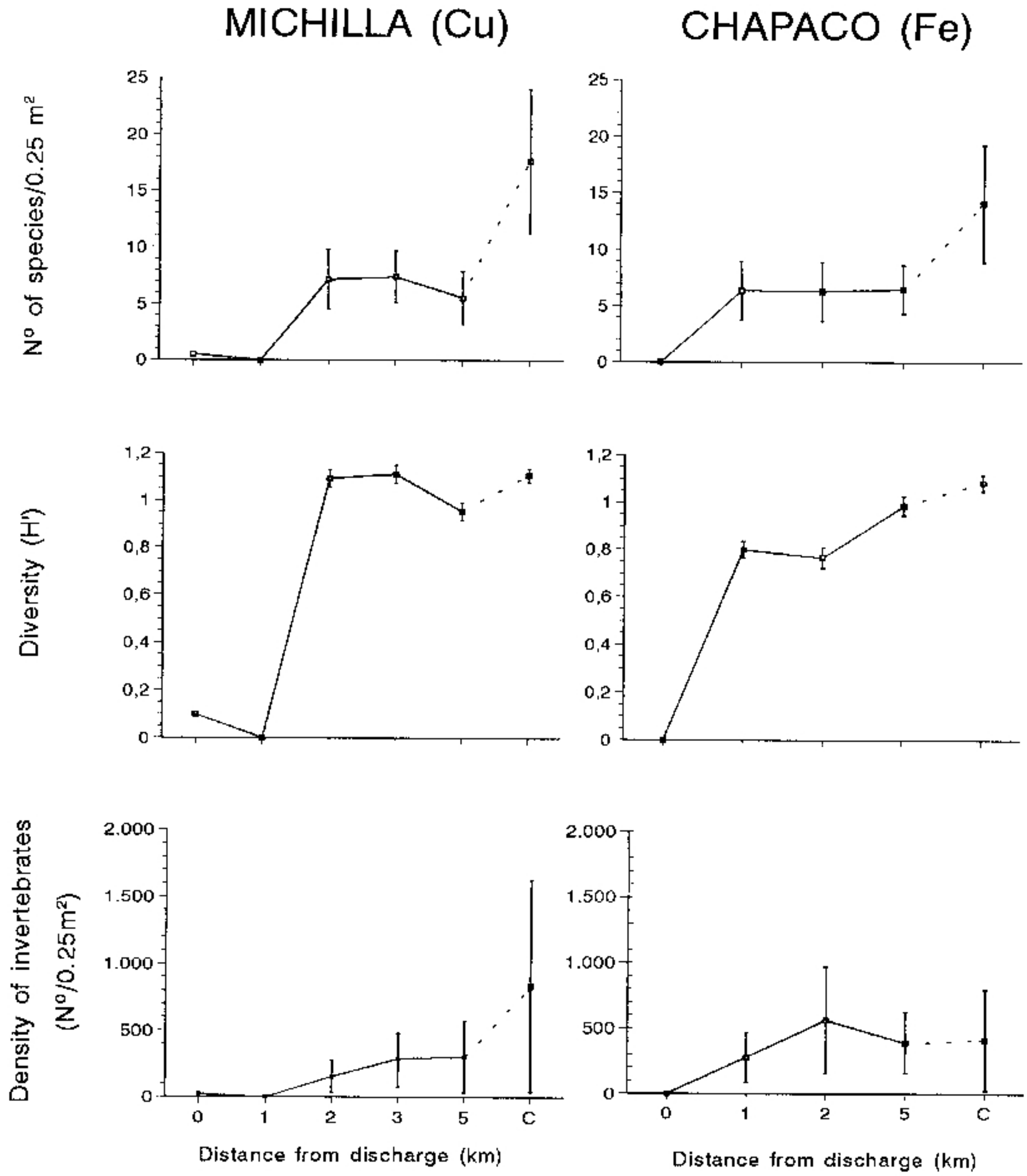

Figure 9. Spatial variability of macroinvertebrate fauna associated with hard substrata between *Lessonia trabeculata* plants exposed to different Cu and Fe concentrations in the field. C = control area. Bars = standard error.

contaminants along an intensity gradient in order to evaluate the mechanisms by which organisms, populations and communities minimize the effects of these agents of environmental perturbation.

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