



Effects of a copper smelter on a grassland community in the Puchuncaví Valley, Chile

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Abstract

A grassland formation has been subjected to pollution generated by the Ventanas copper smelter since 1964 (Puchuncaví Valley, central zone of Chile) with extensive damage to local vegetation and important changes in soil characteristics. The aims of the study were (1) to detect soil parameters that best explain changes observed in plant species richness and abundance and (2) to determine if pollution-derived stresses have also affected regeneration capabilities of plant communities from the soil seed bank. The grassland was quantitatively analysed in terms of physico-chemical soil characteristics, plant species diversity and abundance, and soil seed bank species composition and abundance. Results showed that a decrease in total soil nitrogen explained 13% of the changes detected in plant abundance while soil pH and 0.05 M EDTA extractable copper explained 10% and 7%, respectively, of the vegetation change. It was also found that the pollution has already affected plant species regeneration capabilities from the soil seed bank and the microsite distribution of the seeds in soils. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

Metal smelters cause extensive damage to local vegetation and important changes in soil characteristics (e.g., Gilbert, 1975; Dawson and Nash, 1980; Freedman and Hutchinson, 1980; Wickland, 1980; Macnair and Baker, 1994; Galbraith et al., 1995; Gunn, 1995; Kozlov et al., 1995; Dudka and Adriano, 1997) with the most affected areas immediately surrounding the smelters called the barrens by McCall et al. (1995). These areas are generally characterised by bare and sparsely vegetated land, dominated by pollution resistant plant species, and by severely eroded, acidic and highly metal contaminated soils (Gilbert, 1975; Freedman and Hutchinson, 1980; Amiro and Courtin, 1981; Macnair and Baker, 1994; Galbraith et al., 1995; Gunn, 1995; McCall et al., 1995). It is well-known that heavy metals can cause severe damage to vegetation and even lead to complete death of sensitive individuals (Clarkson and Hanson, 1980; Marschner, 1986; Steffens, 1990; Fernández and Henriques, 1991; Kapustka et al., 1995). Therefore, high heavy metal concentrations in soils has been usually cited as one of the primary factors limiting vegetation establishment and growth in the barrens (e.g.,

Gilbert, 1975; Freedman and Hutchinson, 1980; Amiro and Courtin, 1981; Macnair and Baker, 1994; Galbraith et al., 1995; Gunn, 1995; McCall et al., 1995). It is remarkable that almost all the studies carried out in smelter polluted areas have mainly characterised vegetation changes as the net change in numeric composition of adult fraction of the populations, both in a specific time and place. However, these changes cannot only be explained by the death of adult individuals but also by alterations produced at several stages of the plant life cycle. There is some evidence that atmospheric pollution has negative effects on plant reproduction and regeneration such as decrease in seed production (Banwart et al., 1987; Banwart et al., 1988; Feret et al., 1990; Steubing and Fangmeier, 1991), seed germination and seedling establishment (Paparozzi and Tukey, 1984; Evans, 1984; Ginocchio, 1997). Therefore, when environmental conditions change because of metal smelter pollution and when adult individuals are eliminated, regeneration processes may be altered because there may be no propagules.

The aims of this study were (1) to detect soil parameters that best explain changes observed in a plant community that has been subjected to metal smelter

pollution and (2) to determine if metal smelter pollution has also affected regeneration capabilities of plant communities from the soil seed bank.

2. Materials and methods

2.1. Study site

Mediterranean ecosystems of the Puchuncaví Valley in the coastal area of central Chile have been subjected to massive gaseous and metal-rich particulate pollution from a copper smelter since 1964. The resultant environment degradation has been intense, particularly in the areas immediately surrounding the smelter (the barrenes). These areas are now characterised by bare and sparsely vegetated land and by severely eroded, acidic and heavy metal rich sandy soils (González and Bergqvist, 1986; Alfaro, 1988; Environmental Resources Management, 1993; Pozo, 1993). An area of 3.5 km long and 1.3 km wide, extending in a SSE direction from the copper smelter, was selected as study area. A total of 12 sites, ranging from 2.0 to 5.5 km from the smelter, were selected in the study area to represent a pollution gradient. A 100×100 m area (sampling unit) was defined in each site to carry out soil, vegetation, and soil seed bank samplings as described below.

2.2. Soil sampling and physicochemical analysis

Before the first rains of the season, sixteen soil samples (0–20 cm depth) were taken in the intersections of a 20×20 cm grid overimposed to each sampling unit. Three soil replicas per site were firstly analysed for (1) texture, through particle fractionation (Allen, 1989), (2) OM content, determined after ignition at 500°C for 4 h (Sherman and Fathey, 1990/91) and (3) pH, in a 1:1 soil to 0.01 M CaCl₂ solution (McLean, 1982). Secondly, soil samples were air dried at 65°C, homogenised by grinding, and sieved through a 2 mm mesh. Samples were analysed for total N, Cu, Fe and Zn, extractable sulphate and 0.05 M EDTA extractable Cu following the methodologies described by Allen (1989) or by MISR–SAC (1985). Total metal concentrations (5 M HNO₃) and 0.05 M EDTA extractable Cu were determined by atomic absorption spectrometry.

2.3. Adult vegetation sampling

The identity of all plant species and their relative cover were determined in every sampling unit. The relative cover of shrub species was estimated through the line intercepted method (Armesto and Gutiérrez, 1980) using six parallel 50 m long transects, separated each other by 15 m. The relative cover of each grass and herbaceous species was estimated using 66 quadrats of 0.25×0.25 cm

each, randomly distributed along transects used to estimate shrub relative cover (Goldsmith et al., 1986).

2.4. Soil seed bank sampling

Characterisation of the soil seed bank was used as the most simple way to assess any change already produced in plant regeneration capabilities in the study area. Therefore, soil seed bank was sampled when all plant species had already dispersed their propagules to the environment. The area of sampling units 3 and 11 was subdivided using a grid of 10×20 m and all 40 intersection points were sampled using a soil core sampler of 2.9 cm in diameter and 4.5 cm in depth. Total soil volume taken per sample was 29.7 cm³ while total soil volume taken per sampling unit was 1188 cm³. To separate seeds from soil the standard flotation methodology of Price and Reichmann (1987) was used. The number of seeds per plant species was registered per soil sample, microsite (between and below shrubs) and sampling unit).

2.5. Statistical analysis

Variations in soil OM content, pH, total Cu, Zn, Fe and N concentrations, extractable S and 0.05 M EDTA extractable Cu along the study site were statistically analysed using Spearman correlation coefficients (Siegel and Castellan, 1988). Significance was defined as $p < 0.05$. Variations in total specific richness, native/exotic specific richness and introduced species richness along the study site were statistically analysed using the Spearman correlation coefficient (Siegel and Castellan, 1988). Canonical Correspondence Analysis (CANOCO) was carried out to determine the effect of analysed soil factors on plant species abundance throughout the study area (Ter Braak, 1986; Jongman et al., 1995). Before the analysis, both specific relative cover and soil factor data were ranked and the specific relative cover data were also log transformed. The analysis was carried out using the CANOCO statistical software, version 3.1 (Ter Braak, 1987/92).

Log–Linear analysis was used to test the effects of the distance to the smelter and the microsite (between and below shrubs) on the seed number per plant species. Consequently, 26×2×2 Contingency Tables (species×site×microsites) were used and the statistical significance was evaluated using Chi-square tests based on the traditional Pearson Chi-square statistic (StatSoft, 1993).

3. Results

3.1. Soil factors

There were no statistical differences between the percentages of sand (ANOVA, $F = 0.53$, $P = 0.752$),

clay (ANOVA, $F=0.34$, $P=0.874$), and silt (ANOVA, $F=0.55$, $P=0.735$) measured in all sites. Mean sand, clay and silt percentages in the study units were 75.1%, 10.8% and 14.2%, respectively. There was no significant correlation between soil pH and the distance to the smelter ($r_s = -0.29$, $P=0.366$, Fig. 1a). Soil pH was slightly acidic between sampling units 2 and 12, ranging from 4.4 to 4.8, while it reached a value of approxi-

mately 6.0 near the smelter (unit 1, Fig. 1a). However, the OM content was positively correlated with the distance to the smelter ($r_s = 0.92$, $P=0.001$). As shown in Fig. 1b, the highest OM contents (approximately 2.0%) were found in low polluted sampling units (9–12) while the lowest OM contents (approximately 1.0%) were found in high polluted ones (1–4), near the smelter.

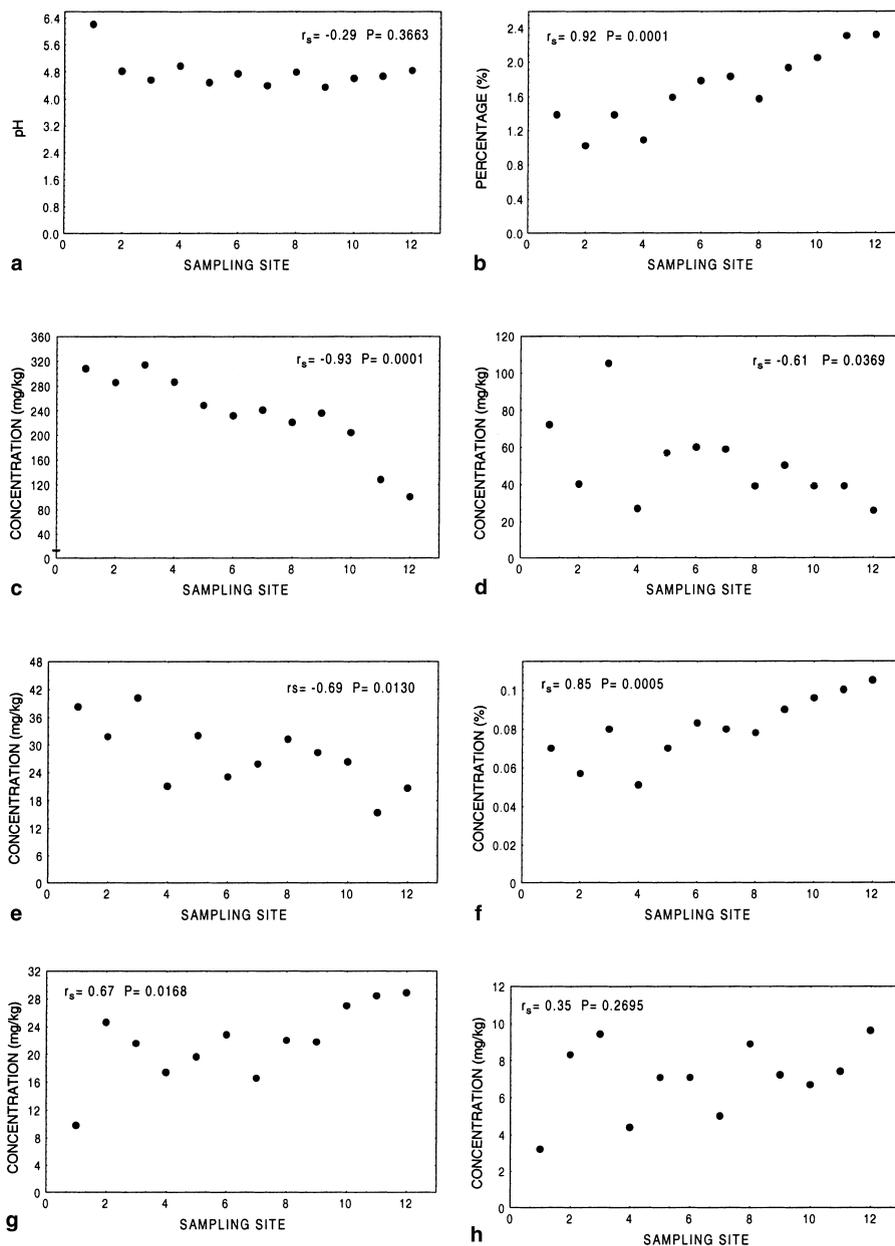


Fig. 1. Physicochemical characteristics of surface soil per sampling unit; (a) pH, (b) organic matter (OM), (c) total Cu, (d) 0.05M EDTA extractable Cu, (e) extractable sulphur, (f) total N, (g) total Fe, and (h) total Zn. Spearman correlation coefficient is indicated and so is its significance ($n = 12$).

Total and 0.05 M EDTA extractable Cu concentrations found in the study site are shown in Fig. 1c and d, respectively. Total copper concentration was higher than extractable Cu concentration in all sampling sites, as expected. Despite the stationary emission source, the copper distribution in soil was very irregular due to microclimatic and topographic variations and also to the effect of vegetation cover. However, both concentrations were significant and negatively correlated with the distance to the smelter ($r_s = -0.93$, $P = 0.001$ for total Cu and $r_s = -0.61$, $P = 0.037$ for extractable Cu). A significant negative correlation was found between extractable S concentration in soil and the distance to the smelter ($r_s = -0.69$, $P = 0.013$). According to Fig. 1e, extractable S concentrations were four times higher in sampling units near the smelter than in units 5.5 km away from the smelter. However, a significant but positive correlation was found between total N concentration and the distance to the smelter ($r_s = 0.85$, $P = 0.0005$, Fig. 1f) and total Fe concentration and the distance to the smelter ($r_s = 0.67$, $P = 0.017$, Fig. 1g). Total N concentration in soil decreased approximately 1.7 times towards the smelter, from 0.1% to 0.06% (Fig. 1f), while total Fe concentration showed a stronger decrease in approximately three times (Fig. 1g).

Although there was no significant correlation between total soil Zn concentration and the distance to the smelter ($r_s = 0.35$, $P = 0.269$), Zn data showed a tendency to decrease towards the smelter (Fig. 1h). The lack of significance could be the result of its irregular distribution along the study area because of microclimatic and topographic variations observed in the study site.

3.2. Plant species richness and abundance

Species richness or the total number of species per site decreased 59.5% towards the smelter, from 42 to 17 species (Fig. 2). This decrease was significant and positively correlated with the distance to the smelter ($r_s = 0.77$, $P = 0.003$). A replacement of plant species along the study site was not detected. Although richness of both native/endemic and introduced species showed a significant decrease toward the smelter (Fig. 2), the number of introduced species decreased more rapidly than the number of native/endemic ones ($r_s = 0.83$, $P = 0.0007$ and $r_s = 0.58$, $P = 0.048$, respectively), indicating introduced species were, in general, very sensitive to the increase in pollution levels and the related edaphic changes produced by the copper smelter. A reduction in very abundant species was detected towards the smelter, from 14.8 species in sampling unit 12–5.5 species in sampling unit 1 (data not shown). The same tendency was found in the number of abundant species which decreased from 20.8 to 7.4 towards the smelter (data not shown).

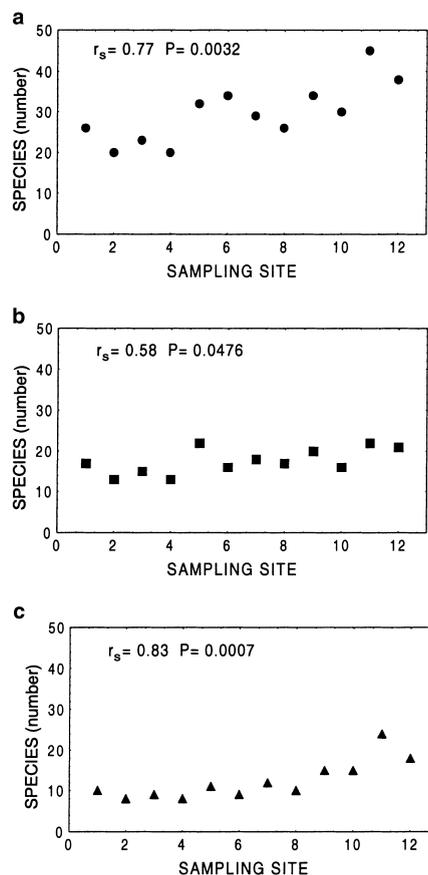


Fig. 2. Relation between plant species richness and the distance to the smelter. Spearman correlation coefficient is indicated in each graph and so is its significance ($n = 12$); (a) total species richness, (b) native/endemic species richness, and (c) introduced species richness.

3.3. Detection of patterns between species abundance and soil factors

Canonical Correspondence Analysis (CCA) of both soil and plant factors indicated that only three soil factors from all analysed were necessary to explain variations observed in plant species abundance along the study site. Specifically, the decrease in total soil N, the low soil pH and the increase in extractable Cu were the main soil factors explaining the decrease in specific plant abundance toward the smelter (Fig. 3). Total N concentration explained 13% of the total variation measured in plant species abundance along the study area, while soil pH and extractable Cu concentration explained an extra 10% and 7% of the measured variation in specific abundance, respectively. Total variation explained by these three factors was 30% from a total of 45% explained by all soil factors considered in the analysis (total Zn, Fe and N, extractable Cu, and S, pH).

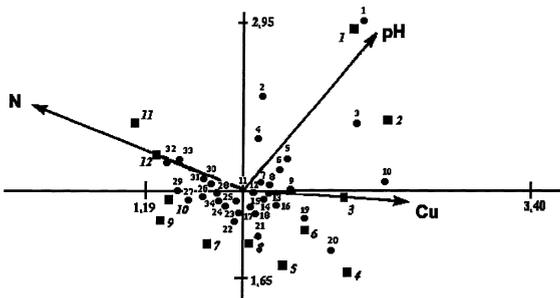


Fig. 3. Canonical ordination diagram with soil factors (arrows), sampling units (solid squares) and plant species (solid circles); the horizontal axis is the first one and the second is the vertical one. Soil factors correspond to total N concentration, extractable Cu and pH. 1 = *Baccharis concava* and *Camassia biflora*; 2 = *Carduus pycnocephalus*; 3 = *Astragalus edmonstonei*; 4 = *Gochnatia foliolosa*; 5 = *Cestrum parqui*; 6 = *Eschscholzia californica* and *Trifolium* spp.; 7 = *Convolvulus* spp.; 8 = *Lolium* spp.; 9 = *Sphaeralcea obtusiloba*; 10 = *Baccharis macraei*; 11 = *Bromus* spp.; 12 = *Argemone subfusiformis*; 13 = *Baccharis linearis*, *Conyza* sp. and *Leucocorine* sp.; 14 = *Oenothera picensis*; 15 = *Noticastrum sericeum*; 16 = *Rhodophala advena*; 17 = *Chenopodium ambrosioides* and *Erodium botrys*; 18 = *Corrigiola* sp.; 19 = *Lupinus microcarpus*; 20 = *Calandrinia compressa*; 21 = *Gnaphalium viravira*; 22 = *Dichondra sericea*; 23 = *Erodium malacoides*; 24 = *Rumex acetosella*; 25 = *Muehlenbeckia hastulata*; 26 = *Carthamus lanatus*; 27 = *Avena barbata* and *Gamochoa* sp.; 28 = *Astragalus berteronianus*, *Solidago chilensis* and *Verbascum virgatum*; 29 = *Bromus cartharticus* and *Hypochaeris glabra*; 30 = *Lotus subpinnatus*; 31 = *Hypochaeris radicata* and *Trichopetalum plumosum*; 32 = *Adesmia tenella*, *Anagallis arvensis*, *Capsella bursa-pastoris*, *Chrysanthemum coronarium*, *Erodium moschatum* and *Raphanus sativus*; 33 = *Erodium cicutarium*; 34 = *Haploppapus uncinatus*.

Relative location between plant species (solid circles) and sampling sites (solid squares) in the CCA ordination diagram indicates the sites where plant species showed highest relative cover (Fig. 3). Position of the species in the diagram was in agreement with the measured values in the field. The arrows in the diagram represent the main soil factors detected by CANOCO (total N, pH and extractable Cu) and their relative location indicates their relationship with plant abundance. Both the location of the arrows and solid circles in the CCA diagram explained 91% of the variance of the weighted means of the 51 plant species by the six soil factors considered, being 0.27 the sum of the eigenvalues.

The length of the arrow indicates the importance of soil factors and the perpendicular projection of solid circles on each arrow indicates the species distribution in all soil gradients considered. In the first axis of the CCA diagram the species followed a N gradient that decreased from left to right of the diagram, superimposed with an opposite gradient of extractable Cu; in the second axis the species followed a pH gradient that decreases from top to down of the diagram. For instance,

Baccharis macraei was more abundant in habitats with high extractable Cu concentrations and low total N concentration, *Baccharis concava* and *Camassia biflora* were more abundant in low acidic soils, while *Erodium cicutarium* was more abundant in habitats with low extractable Cu but high total N concentration.

3.4. Soil seed bank

Table 1 shows the seed number per plant species and microsite (between and below shrubs) quantified in soil seed banks of sampling units 3 and 11. Although total seed number was similar in both sampling units (5766 in site 3 and 6660 in site 11), their microsite distribution was different. Soil seed bank was more abundant below than between shrubs in the most polluted site (unit 3) while it was more abundant between shrubs in the less polluted site (unit 11).

Seed species richness was 1.5 times greater in unit 11 than in unit 3 (25 vs. 17 species, respectively; Table 1). Specifically, few species showed very low or very high seed numbers in sampling unit 11 and most of them were well represented in the soil seed bank. However, few species showed high seed numbers in soil seed bank of unit 3 and most of them were less represented. The identity of the most abundant species in soil seed bank differed in both units, with the exception of *B. linearis* (Table 1). In unit 3, seeds of *Sphaeralcea obtusiloba* were the most abundant ones while in unit 11, seeds of *Centaurea melitensis*, *Chrysanthemum coronarium* and *Conyza* sp. were the most abundant ones (Table 1).

The log-linear analysis of the $26 \times 2 \times 2$ tables indicated that the triple interrelation model was the one that included the lowest number of interactions between the considered factors ($X^2_{(0;0.05)} = 0.001$ and $P = 1.00$). This result indicates that the amount of seeds per plant species present in the soil seed bank was related to the distance to the polluting source and the microsite, but in a multiplicative way. Therefore, environmental gradient generated by the copper smelter has not only affected adult plant abundance but has already affected soil seed bank abundance and microdistribution and so the regeneration capability of the system.

4. Discussion

As a consequence of the high and continuous deposition of pollutants on soils of the study area during the last 30 years, several environmental gradients have been created in concordance with results of other areas that have also been perturbed by metal smelters (e.g., Galbraith et al., 1995; McCall et al., 1995; Helmisaari et al., 1995; Lukina and Nikonov, 1995). The results of this study clearly indicate that, at least, three soil gradients (N, OM and pH) are able to explain changes produced

Table 1

Plant species present in the soil seed bank of sampling sites 3 and 11. The specific number of seed per sampling site and microsite in 1188 cm³ of soil is indicated

Species	Between shrubs		Below shrubs	
	Site 11	Site 3	Site 11	Site 3
<i>Baccharis concava</i>	0	15	0	73
<i>Baccharis linearis</i>	386	46	163	229
<i>Baccharis macraei</i>	23	0	12	0
<i>Cestrum parqui</i>	5	1	0	4
<i>Gochmatia foliolosa</i>	14	0	2	0
<i>Haploppapus uncinatus</i>	25	1	2	3
<i>Sphaeralcea obtusiloba</i>	106	597	359	4014
<i>Argemone subfusiformis</i>	14	1	1	3
<i>Carthamus lanatus</i>	3	0	0	0
<i>Centaurea melitensis</i>	920	0	259	3
<i>Chrysanthemum coronarium</i>	726	0	115	0
<i>Chenopodium ambrosioides</i>	138	104	27	48
<i>Conyza</i> sp.	434	0	111	0
<i>Convolvulus</i> sp.	11	6	0	7
<i>Erodium botrys</i>	3	21	1	40
<i>Erodium cicutarium</i>	370	0	105	0
<i>Eschscholzia californica</i>	109	15	31	25
<i>Hypochaeris glabra</i>	74	0	25	0
<i>Hypochaeris radicata</i>	14	1	7	3
<i>Marrubium vulgare</i>	247	0	80	0
<i>Noticastrum sericeum</i>	37	0	8	15
<i>Oenothera picensis</i>	221	40	111	116
<i>Rumex acetosella</i>	163	48	60	42
<i>Solidago chilensis</i>	179	0	59	0
<i>Verbascum virgatum</i>	272	14	122	16
Grasses	358	57	135	145
Total	4865	980	1795	4786

in plant species abundance along the study site. However, relative importance of all three gradients in determining vegetation changes is different. The CCA analysis indicates that soil N/OM gradient is more important to explain the decrease in plant species abundance than soil Cu/S gradient. This finding is very important because it indicates metal increase in soils may not be the main soil stress factor limiting plant establishment and growth near Ventanas copper smelter, as has been suggested for other metal smelter polluted areas (e.g., Freedman and Hutchinson, 1980; Amiro and Courtin, 1981; Kryuchon, 1993; Macnair and Baker, 1994; Brakenhielm and Qinghong, 1995; Galbraith et al., 1995; Gunn, 1995; Helmisaari et al., 1995; Kapustka et al., 1995; McCall et al., 1995).

Cu phytotoxicity was expected to be found in the study area due to both a net increase in extractable Cu from 20 mg/kg in less polluted sites to 60 mg/kg in high polluted sites and high solubility of copper ions because of the low buffering capacity of the soils of the area (Rovira, 1984; Alfaro, 1988; Davies, 1992; Environmental Resources Management, 1993; Pozo, 1993; Lagos and Ibañez, 1993), but the results do not support this. This

may be due to the surface accumulation of metals in soils of the study site (the first 5 cm; Ginocchio, unpublished data), which plant roots may be able to avoid. However, the continuous rise in surface soil metal concentrations from low to high levels in Puchuncaví Valley and their slowly migration to deeper soil horizons (González and Bergqvist, 1986; González, 1989) may determine increasing selective forces for metal tolerant plants in the future.

The greater importance of the N/OM gradient may be the result of the high percentage of introduced species in the study site (42.6%) that have higher nitrogen requirements than most of the native species growing in the area (Ramírez et al., 1991). Although soil N gradient corresponds to a 0.04% decrease, soil N concentration of 0.06% measured at the most polluted sites imposes a strong nutrient deficiency stress to most introduced species. However, N concentration measured along the study area is in the 0.02–0.21% total N concentration range described for natural Mediterranean ecosystems (Grey and Schlesinger, 1981; Groves et al., 1983), that may not represent a nutrient deficiency stress to native plant species. This may explain the higher decrease in

introduced plant species richness than native/endemic plant species richness.

Although a significant correlation between soil pH and the distance from the smelter was not detected, all sampling units were slightly acidic (a mean of 4.8) when compared with the range of 6–7 described for unpolluted soils nearby the study area (Environmental Resources Management, 1993; Lagos and Ibañez, 1993). Increase in soil acidity may affect plant species richness and abundance not only by direct negative effects but also by increasing both nutrient solubility and nutrient leaching from soils (Chapin, 1991).

Thirty percent of vegetation variance was explained by total soil N, pH and extractable soil Cu, as indicated by the CCA. This result points out that it may be other environmental factors determining vegetation changes in the study area that were not considered and quantified in this study. There is evidence in the literature showing that long-term SO₂ fumigations and acid rain derived from metal smelter pollution and other pollution sources may also have important phytotoxic effects (e.g., Larcher, 1995; Ulrich, 1983; Schütt, 1986; Ulrich, 1986; Banwart et al., 1987; Krause, 1988; Gruszka et al., 1990). Gaseous pollutant, acid mist and acid rain have direct negative impacts on vegetation and indirect impacts through changes in physicochemical soil characteristics and other environmental factors that represent important stresses for plant establishment and growth (Abrahamsen, 1983; Ginocchio, 1997; Gruszka, 1991; MacLean, 1990). The study site has been also subjected to massive SO₂ fumigation during the last 30 years because of a lack of environmental regulations in Chile until 1992. Therefore, acute and chronic SO₂ fumigation may be mainly responsible for defoliation, stunting, reduced productivity and death of sensitive plant species in the Ventanas copper smelter hinterland. Besides the effects produced by direct gaseous fumigation on plant canopies, acid precipitation may be an important added factor in the area as indicated by the increase in soil acidity towards the smelter.

Finally, effects of pollution-derived stresses cannot only be analysed through presence/absence and abundance of adult plant species in a determined area but they can also be analysed through changes produced in the soil seed bank (Sanders et al., 1995; Zonneveld, 1982). The results of this study indicate a good relation between species presence in soil seed bank and specific composition of adult vegetation in sampling sites. Consequently, regeneration capabilities from the soil seed bank in highly polluted areas may already be restricted to pollution resistant species. Changes in soil seed bank microsite distribution along the study site may be the result of increased wind erosion and shrub relative cover toward the smelter; low and densely packaged shrubs characteristic in high polluted areas of

the Puchuncaví Valley may act as physical barriers for wind erosion and so as seed collectors.

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