

Trends in the Levels of Metals in Soils and Vegetation Samples Collected Near a Hazardous Waste Incinerator

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Abstract. In 1998 and 2001, the levels of a number of elements (As, Be, Cd, Cr, Hg, Mn, Ni, Pb, Sn, Tl, and V) were determined in 40 soil and 40 herbage samples collected near a new hazardous waste incinerator (HWI) (Constantí, Catalonia, Spain). In 2003, soil and herbage samples were again collected at the same sampling points in which samples had been taken in the previous surveys. During the period 1998–2003, As, Be, Cr, Ni, and V levels showed significant increases in soils. In contrast, the levels of Cd, Hg, and Sn significantly decreased. With respect to herbage, while Cr, Mn, and V concentrations significantly increased, those of As levels diminished. On the other hand, human health risks derived from metal ingestion and inhalation of soils were also assessed. In relation to noncarcinogenic risks, all elements presented a value inside the safe interval. In turn, Cd and Cr were also in the safe interval of carcinogenic risks, whereas in contrast As levels clearly exceeded the regulatory limits concerning carcinogenic risks. According to the results of the previous (2001) and current (2003) surveys, the fluctuations in the metal concentrations suggest that the influence of the HWI is minimal in relation to other metal pollution sources in the area.

Waste management facilities in general, and incinerators in particular, have been traditionally affected by the NIMBY (Not In My Back Yard) syndrome (Kuhn and Ballard 1998). Although in comparison with other treatments for processing municipal solid waste (MSW) and hazardous waste (HW), incineration has multiple advantages (i.e., volume reduction, energy recovery, elimination of pathogen agents), public opposition to the siting and permitting of MSW and HW incinerators has been considerable (Chang *et al.* 2002, 2003; Domingo 2002a, 2002b; Hamer 2003). The main concern is related to the potential adverse consequences of the emission of pollutants for both the environment and public health (Schuhmacher *et al.* 1997a, 1997b; Domingo *et al.* 2002c).

Combustion processes have been catalogued as important contributors to environmental metal pollution. Among these processes, special attention has been paid to incineration

(Hasselriis and Licata 1996; Thipse and Dreizin 2002). The number of hazardous waste incinerators (HWI) is notably lower than that of municipal solid waste incinerators (MSWI), and the volume of waste to be treated is also remarkably different. However, taking into account the potential number and variety of toxic residues contained in industrial wastes, these are expected, in principle, to be more dangerous than municipal wastes (van Veizen *et al.* 2002).

Environmental monitoring programs are common tools to control the state of pollution in a particular area (Rumbold *et al.* 1997; Morselli *et al.* 2002; Chang *et al.* 2003). These programs are used to assess the contribution of a potential contaminant source on the global environment. Because they can be easily collected and stored, soil and vegetation are two of the most standardized environmental monitors (Mumma *et al.* 1990; Klumpp *et al.* 1994, 2003; Moraes *et al.* 2002). Soil and vegetation have been widely used as cumulative matrices of long-term and short-term exposure, respectively, to environmental pollutants (Meneses *et al.* 1999; Domingo *et al.* 1999, 2001; Schuhmacher *et al.* 1996, 2000, 2002, 2003; Nadal *et al.* 2004).

In 1996, the construction of a HWI in Constantí (Tarragona, Spain) was initiated. Regular operations started in 1999. Because this facility was the first, and up until now the only HWI in Spain, the concern about its potential environmental impact and health risks has been, and still remains, considerable in public opinion. In response to that concern, a wide preoperational monitoring program was designed to evaluate the potential impact of emissions from the new HWI on the neighborhood, as well as to assess the health risks to the population living near the facility. Generally, evaluation of HWI stack emissions has been focused on heavy metals, semivolatile and volatile compounds, with special attention being paid to metals (carcinogenic elements such as cadmium and chromium are of particular concern), and dioxins and furans (Lisk 1988; Sedman and Esparza 1991; Dempsey and Oppelt 1993; Schuhmacher *et al.* 2002). A baseline survey was finished in 1998, just before the HWI began operating. Soil and herbage samples were collected in the vicinity of the facility under construction and were analyzed for metals (Llobet *et al.* 2000) and dioxins and furans (Schuhmacher *et al.* 1997a, 1998, 2000).

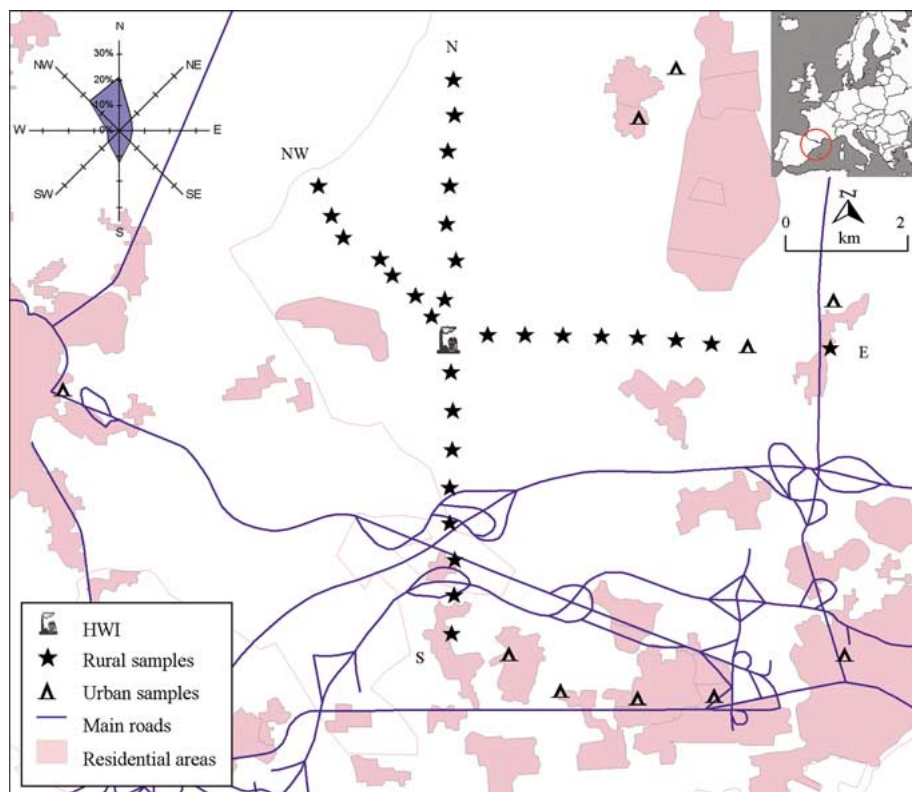


Fig. 1. Sampling points of the area under study and wind rose (Departament de Medi Ambient 2002).

Table 1. Metal concentrations ($\mu\text{g/g} \pm \text{SD}$) in soil and herbage samples collected near the HWI^a

Soil	1998	2001	2003	1998–2003%	2002–2003%
As	6.71 \pm 2.18	5.75 \pm 1.53	8.54 \pm 3.71	27.3*	48.5***
Be	0.40 \pm 0.23	0.50 \pm 0.15	0.56 \pm 0.28	40.0***	12.0
Cd	0.26 \pm 0.17	0.26 \pm 0.20	0.22 \pm 0.15	-15.4*	-15.4
Cr	16.01 \pm 5.01	13.31 \pm 4.75	21.64 \pm 11.27	35.2**	62.6***
Hg	0.16 \pm 0.11	ND	0.08 \pm 0.22	-50.0***	—
Mn	280.4 \pm 84.5	236.9 \pm 69.3	320.5 \pm 126.4	14.3	353***
Ni	15.16 \pm 4.66	15.56 \pm 6.68	29.87 \pm 11.92	97.0***	92.0***
Pb	41.46 \pm 32.58	46.36 \pm 29.04	40.07 \pm 24.83	-3.4	-13.6
Sn	0.22 \pm 0.18	0.12 \pm 0.09	0.19 \pm 0.34	-13.6***	58.3
Tl	0.12 \pm 0.03	0.11 \pm 0.03	0.16 \pm 0.11	33.3	45.5**
V	18.94 \pm 5.34	16.42 \pm 4.09	29.24 \pm 17.03	54.4***	78.1***
Herbage	1998	2001	2003	1998–2003%	2002–2003%
As	0.11 \pm 0.04	ND	0.07 \pm 0.06	-36.4***	—
Be	ND	ND	ND	—	—
Cd	0.05 \pm 0.01	0.04 \pm 0.05	0.02 \pm 0.02	-60.0	-50.0**
Cr	0.23 \pm 0.17	0.28 \pm 0.40	0.32 \pm 0.21	39.1*	-14.3***
Hg	0.23 \pm 0.09	ND	ND	—	—
Mn	37.7 \pm 15.4	39.9 \pm 18.3	49.3 \pm 16.1	30.6**	23.7
Ni	0.59 \pm 0.25	0.77 \pm 1.71	0.58 \pm 0.34	-1.7	-24.7*
Pb	1.03 \pm 1.21	0.50 \pm 0.30	0.63 \pm 0.54	-38.8	26.0
Sn	0.12 \pm 0.03	0.05 \pm 0.02	0.11 \pm 0.17	-8.3	120.0*
Tl	ND	ND	ND	—	—
V	0.19 \pm 0.13	0.38 \pm 0.20	0.38 \pm 0.17	100.0***	0.0

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

ND = not detected.

^a Data for 1988 (baseline survey), 2001, and 2003 and percentages of variation.

In 2001, 3 years after the baseline survey, the concentrations of metals and dioxins and furans were again determined in soil and herbage samples collected at the same points in which

samples had been taken in the baseline survey (unpublished data). Recently, samples of both matrices were again collected and analyzed for metal levels. The results are here reported

Table 2. Metal concentrations ($\mu\text{g/g} \pm \text{SD}$) in urban and rural soil samples collected in 1998 and 2003

1998	Urban	Rural	<i>p</i>
As	6.15 \pm 1.21	6.90 \pm 2.41	NS
Be	0.44 \pm 0.15	0.38 \pm 0.25	NS
Cd	0.38 \pm 0.31	0.22 \pm 0.06	NS
Cr	16.23 \pm 4.66	15.94 \pm 5.20	NS
Hg	0.26 \pm 0.16	0.13 \pm 0.06	<0.05
Mn	262.0 \pm 60.8	286.6 \pm 91.12	NS
Ni	14.59 \pm 3.30	15.34 \pm 5.08	NS
Pb	59.56 \pm 54.60	35.42 \pm 18.75	NS
Sn	0.36 \pm 0.30	0.17 \pm 0.09	<0.05
Tl	0.11 \pm 0.03	0.13 \pm 0.04	NS
V	18.35 \pm 4.04	19.14 \pm 5.75	NS
2003	Urban	Rural	<i>p</i>
As	7.57 \pm 2.86	8.87 \pm 3.94*	NS
Be	0.43 \pm 0.14	0.60 \pm 0.30*	<0.05
Cd	0.22 \pm 0.09	0.22 \pm 0.17*	NS
Cr	17.04 \pm 3.65	23.17 \pm 12.53*	NS
Hg	0.04 \pm 0.04*	0.09 \pm 0.26*	NS
Mn	268.6 \pm 72.4	337.8 \pm 136.5	NS
Ni	25.38 \pm 7.76*	31.37 \pm 12.14*	NS
Pb	47.71 \pm 26.45	37.53 \pm 24.19	NS
Sn	0.17 \pm 0.23	0.20 \pm 0.37*	NS
Tl	0.12 \pm 0.04	0.17 \pm 0.13	<0.05
V	23.42 \pm 5.27*	31.18 \pm 19.13*	NS

NS: differences not statistically significant ($p > 0.05$).

Asterisks indicate significant differences ($p < 0.05$) for the same kind of samples (urban or rural) between the 1998 and 2003 surveys.

Table 3. Metal concentrations ($\mu\text{g/g} \pm \text{SD}$) in urban and rural herbage samples collected in 1998 and 2003

1998	Urban	Rural	<i>p</i>
As	0.12 \pm 0.07	0.10 \pm 0.02	NS
Be	ND	ND	—
Cd	0.05 \pm 0.01	0.05 \pm 0.01	NS
Cr	0.28 \pm 0.34	0.21 \pm 0.06	NS
Hg	0.23 \pm 0.09	0.23 \pm 0.10	NS
Mn	27.47 \pm 9.24	41.2 \pm 15.6	<0.05
Ni	0.68 \pm 0.35	0.56 \pm 0.21	NS
Pb	1.57 \pm 2.25	0.86 \pm 0.52	NS
Sn	0.11 \pm 0.03	0.12 \pm 0.03	NS
Tl	ND	ND	—
V	0.22 \pm 0.18	0.17 \pm 0.11	NS
2003	Urban	Rural	<i>p</i>
As	0.07 \pm 0.04	0.08 \pm 0.06*	NS
Be	ND	ND	—
Cd	0.02 \pm 0.01	0.02 \pm 0.02	NS
Cr	0.33 \pm 0.32	0.31 \pm 0.17*	NS
Hg	ND	ND	—
Mn	42.6 \pm 11.9*	51.5 \pm 16.8*	NS
Ni	0.59 \pm 0.35	0.57 \pm 0.34	NS
Pb	0.80 \pm 0.79	0.58 \pm 0.43	NS
Sn	0.04 \pm 0.02*	0.14 \pm 0.19	<0.05
Tl	ND	ND	—
V	0.37 \pm 0.15	0.38 \pm 0.17*	NS

NS: differences not statistically significant ($p > 0.05$).

Asterisks indicate significant differences ($p < 0.05$) for the same kind of samples (urban or rural) between the 1998 and 2003 surveys.

and compared with those found in the 2001 survey and the baseline surveys. On the other hand, the present study is also focused on establishing the health risks of metals for the population living in the neighborhood of the HWI.

Materials and Methods

Sampling

In April 2003, soil samples were collected at the same 40 sampling sites used in the baseline survey (1998) and the 2001 survey (Llobet *et al.* 2000). These points were selected taking into account the main wind directions and in a radius of 7 km from the HWI (Figure 1). Ten samples were collected in urban zones, whereas the remaining 30 were considered to belong to rural zones. Approximately five subsamples were collected as bulk samples at the same time within approximately 20 m² in each sampling site. Soil samples were taken from the upper 3 cm of soil and stored in polyethylene bags for easy handling. In the laboratory, they were dried at room temperature and sieved through a 2-mm-mesh screen in order to obtain a homogeneous grain distribution.

Vegetation samples were also taken at the same 40 sampling points and at the same time as soil samples (April 2003). No rainfall was observed during the days before collection of samples. Herbage (*Pipatherum paradoxum* L) samples were obtained by cutting at about 5 cm from the ground. They were immediately stored in a double-aluminum fold and dried at room temperature.

Analytical Procedure

Approximately 0.5 g of dried soil and herbage samples were treated with 5 ml of HNO₃ (65% Suprapur, E. Merck, Darmstadt, Germany) in hermetic Teflon bombs and maintained at room temperature for 8 h. Subsequently, they were heated at 80°C for 8 h. After cooling, solutions were filtered and made up to 25 ml with deionized water (Meneses *et al.* 1999; Schuhmacher *et al.* 2003).

The concentrations of arsenic (As), beryllium (Be), cadmium (Cd), chromium (Cr), mercury (Hg), manganese (Mn), lead (Pb), tin (Sn), thallium (Tl), and vanadium (V) in soils were determined by inductively coupled plasma spectrometry (ICP-MS, Perkin Elmer Elan 6000), while atomic absorption spectrometry with graphite furnace atomization (Varian spectrophotometer, Spectra A-30) was used to determine nickel (Ni) concentrations. The levels of As, Be, Cd, Hg, Mn, Pb, Sn, and Tl in herbage samples were assessed by ICP-MS, while the concentrations of Cr, Ni, and V were determined by atomic absorption spectrometry with graphite furnace atomization.

The limits of detection (LOD) for soils and herbage were the following: 0.1 $\mu\text{g/g}$ for As; 0.025 $\mu\text{g/g}$ for Cd, Mn, Ni, Pb, and Tl; 0.05 $\mu\text{g/g}$ for Hg and Sn; and 0.25 $\mu\text{g/g}$ for Be. In herbage, detection limits of Cr and V were 0.04 and 0.1 $\mu\text{g/g}$, respectively, whereas in soils, the LOD for these elements was 0.25 $\mu\text{g/g}$. The accuracy of the methodology was checked by determining the levels of duplicate samples, as well as those of blanks (control samples). Moreover, a reference material (Lobster hepatopancreas, NRC Canada, TORT 2), which was run after every 10 samples, was also used to check for drift in the sensitivity of the instrument. Recovery rates ranged from 79% to 123% for soils and from 82% to 124% for vegetation.

Statistics

In the case of values under the respective detection limits, concentrations were assumed to be one-half of the limit of detection

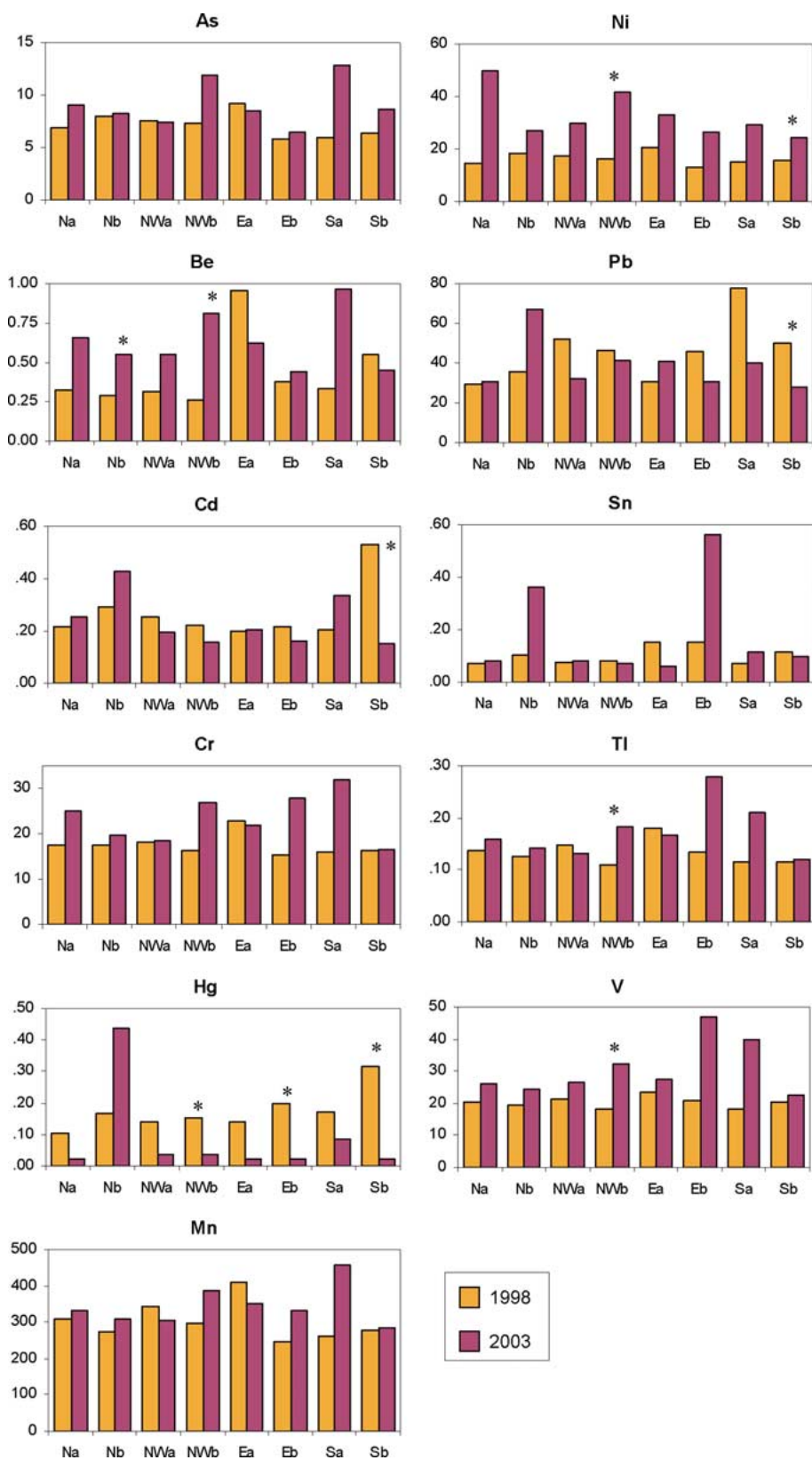


Fig. 2. Concentrations of metals in soils (µg/g) according to the directions of the wind (N, NW, E, and S) and the distance to the HWI (zones *a* and *b*). An asterisk means significant differences between 1998 and 2003.

(ND = 1/2 LOD). Statistical significance of the data was computed by one-way analysis of variance followed by Student's *t*-test or by the Kruskal-Wallis test. A probability of 0.05 or lower was considered significant. All the analyses were done using the statistical package

SPSS 11.0. A multivariate analysis was also done. Data were evaluated through principal component analysis (PCA), which is a multivariate technique for reducing matrices of data to their lowest dimensionality. It allows identification of the number of significant

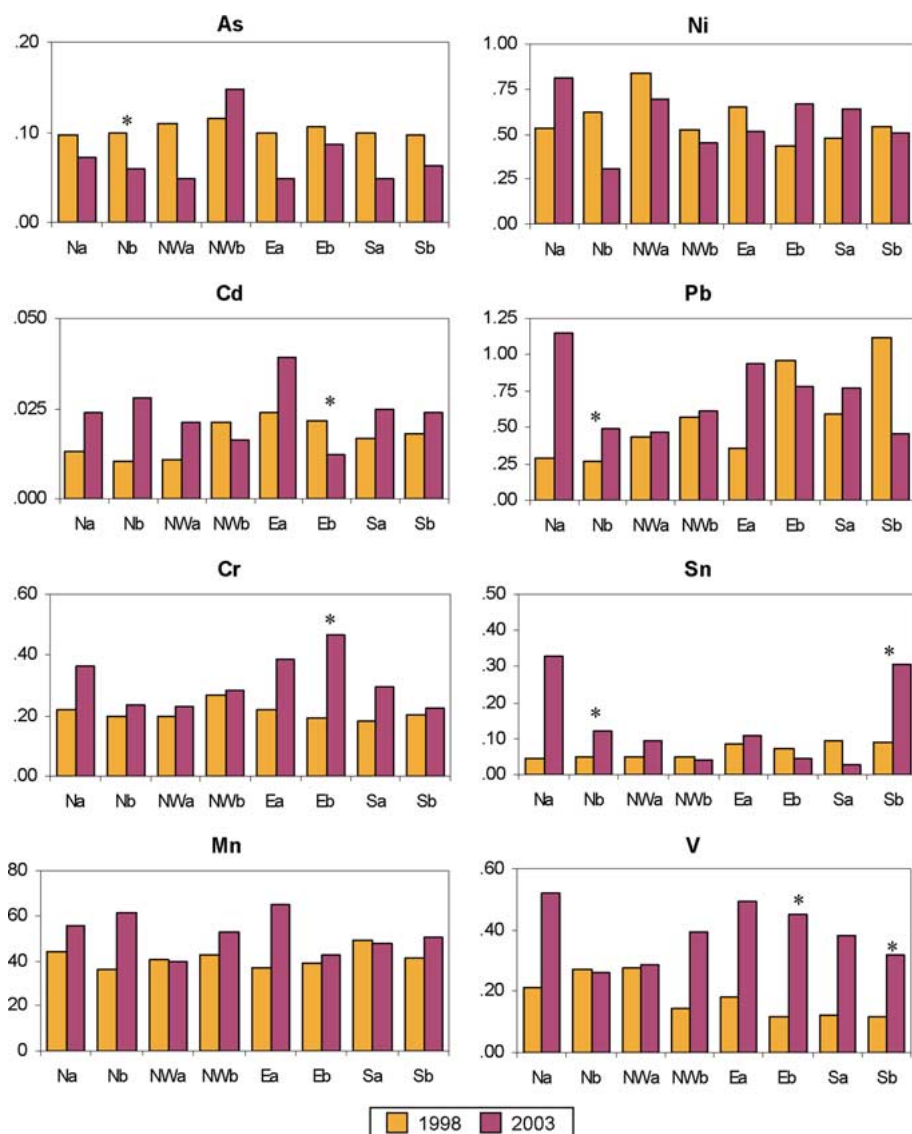


Fig. 3. Concentrations of metals in herbage ($\mu\text{g/g}$) according to the directions of the wind (N, NW, E, and S) and the distance to the HWI (zones *a* and *b*). An asterisk means significant differences between 1998 and 2003.

factors (principal components) and use of this information for classification.

Results and Discussion

The concentrations of metals in soils and herbage collected in 2001 and 2003 in the vicinity of the new HWI, together with the results of the baseline (1998) survey, are shown in Table 1. The percentages of variation during the periods 1998–2003 and 2001–2003 are also given. During the period 1998–2003, As, Be, Cr, Ni, and V levels showed significant increases in soils. In contrast, the levels of Cd, Hg, and Sn significantly diminished. With respect to herbage, Cr, Mn, and V concentrations were significantly increased, while As levels significantly diminished ($p < 0.001$). Although the 2003 concentrations of Cd, Pb, and Sn in vegetation were lower than those of the baseline (1998) study, the differences did not reach the level of statistical significance. Vanadium was the only element showing a similar tendency in both matrices:

increases of 54.4% and 100% in soils and herbage, respectively. In general terms, important fluctuations were observed in the levels of metals in soils and vegetation between the 1998 and 2003 surveys. It must be taken into account that in addition to combustion processes, environmental levels of metals can be notably influenced by a remarkable number of different emission sources. The HWI is located in an industrial zone, where several chemical and petrochemical companies are settled in. Moreover, the area is surrounded by a highway and several important roads. Consequently, the potential impact of other sources must be specially considered. On the other hand, no statistically significant correlation (Pearson) between soil and herbage concentrations was found for any of the analyzed elements. This means that root uptake of heavy metals by plants can be considered negligible. This was an expected finding, because only the A soil horizon (upper layer) was sampled. Likewise, the lack of a homogeneous change between soil and vegetation levels also means that other potential emission sources, different from incineration, could be even more important than they were supposed.

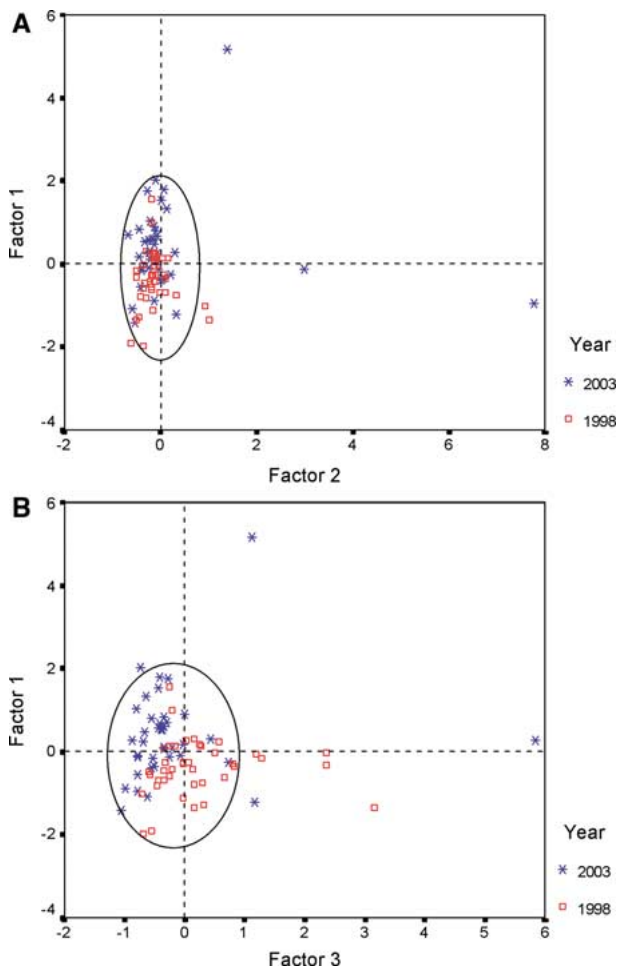


Fig. 4. (a) Principal component analysis. Plot PC1/PC2 for metals in soil samples. (b) Principal component analysis, Plot PC1/PC3 for metals in soil samples.

Tables 2 and 3 summarize the concentrations of metals in soils and herbage, respectively, according to the specific zones of sampling, urban or rural. Data are given for the 1998 and 2003 surveys. In the present study, the levels of all elements were higher in rural soils than in those collected in urban zones. The differences were statistically significant for Be and Tl in 2003, whereas in the baseline survey the level of significance had been reached only for Hg and Sn. The study of the temporal variation of the data shows that the rural soil samples collected in 2003 presented higher metal concentration than those found in 1998. The differences were statistically significant for all elements, with the exception of Mn, Pb, and Tl. The homogeneous increase in the concentrations observed in rural samples was not noted in those collected in urban zones, in which Ni and V levels showed significant increases, while Hg concentrations decreased (Table 2).

In vegetation, the differences according to the area of collection were not so evident. Thus, only Sn levels found in rural samples were significantly higher than those observed in urban samples. Manganese concentrations were significantly increased between 1998 and 2003 in both urban and rural samples. Other elements also presented significant changes during this period in rural samples. The levels of Cr increased, while

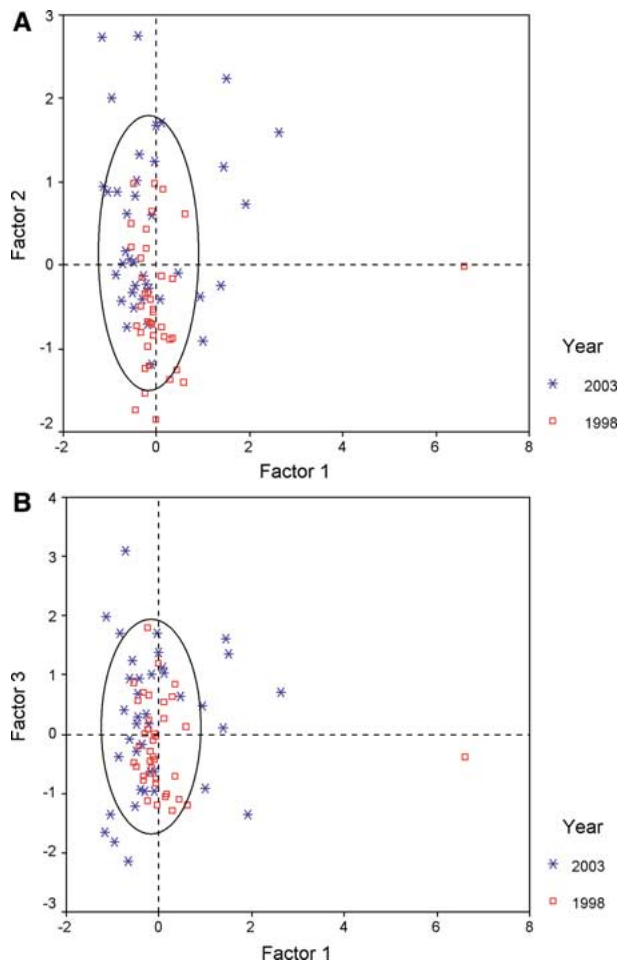


Fig. 5. (a) Principal component analysis. Plot PC1/PC2 for herbage samples. (b) Principal component analysis. Plot PC1/PC3 for herbage samples.

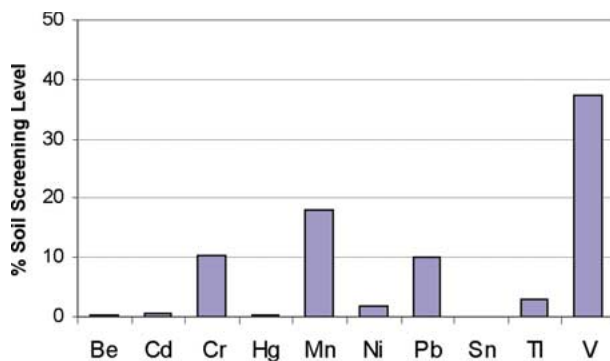


Fig. 6. Noncarcinogenic risk: Comparison between metal concentrations in soils collected in the vicinity of the HWI and Preliminary Remediation Goals.

those of V decreased. In turn, only Sn concentrations showed a significant decrease in urban samples.

To assess the influence of the HWI on the area under its direct influence, sampling points collected at the main wind directions (N, NW, E, and S) were distributed into 2 groups:

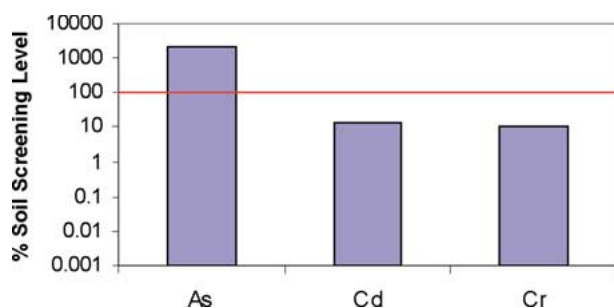


Fig. 7. Carcinogenic risk: Comparison between levels of carcinogenic elements in soils collected in the vicinity of the HWI and Preliminary Remediation Goals.

“a” (those located up to 1500 m from the stack), and “b” (those located at greater distances). This classification was based on data such as the height of the HWI stack (55 m) and the wind regime of the zone (predominant winds: N and NW). A comparison of the 1998 and 2003 metal levels in soil and herbage samples is depicted in Figures 2 and 3, respectively. For soils, significant changes were not found for any wind direction in the “a” zone. With respect to the “b” area, significant changes were noted for Be, Hg, Ni, Tl, and V in the NW direction, as well as for Cd, Hg, Ni, and Pb in the S direction. Significant differences at the N, S, and E directions were also observed for various elements in herbage samples (Figure 3).

The significant differences in metal concentrations appeared mainly at distances more than 1.5 km from the plant. It might be an indicator that the HWI is not the main contributor of the presence of metals into the environment of the area under evaluation. Data fluctuations would be due to the presence of other pollution sources (traffic, industrial activities, etc.), and/or to the environmental variations of these elements in the zone. In general terms, the current metal concentrations in soil and vegetation were very similar to those obtained in previous studies in the vicinity of a MSWI also operating in Tarragona (Llobet *et al.* 1999, 2002), and in an important petrochemical complex located in Tarragona County (Nadal *et al.* 2004). They were also similar to those found in recent years by our research group in samples collected in zones under the influence of another MSWI (Schuhmacher *et al.* 1997a; Meneses *et al.* 1999) and a cement plant (Schuhmacher *et al.* 2003) of Catalonia.

In order to study temporal changes of the heavy metals concentration in soil and vegetation, multivariate analysis (PCA) was carried out. The input data corresponded to 80 samples collected in 1998 and 2003. In soils, PCA provided a three-dimensional model, which accounted for 81.3% of the variance. The first principal component (PC), which explained 34.7% of the variance, was positively correlated with As, Be, Mn, Cr, and Ni. The second PC (25.3% of the variance) was correlated with Sn, Tl, and V. Finally, the third PC (21.3% of the variance) showed a correlation with Cd, Hg, and Pb. With regard to herbage samples, the three-dimensional model accounted for 66.8% of the variance. The first component correlated positively with Cr, As, Pb, and V and explained 37.6% of the variance. The second PC was correlated with Ni and the third PC with Mn and Hg (15.1% and 14.1% of the variance, respectively). Scatter plots for soil and vegetation samples are

depicted in Figure 4a and 4b and in Figure 5a and 5b, respectively. In general, most soil and herbage samples form a cluster. However, no characterization was observed according to the year of collection. Some samples showed high concentrations of some components, although only a few of them were collected near the incinerator. It can be determined that these samples could be contaminated by other emission sources of metal different from the HWI assessed here. Consequently, PCA allowed establishing again that the influence of the incinerator over the surrounding environment could not be considered more important than other potential sources.

Risk assessment consisted of comparing the current metal concentrations in soils with Preliminary Remediation Goals (PRG), considered as safe values for people living in residential areas (US EPA 2004). In relation to noncarcinogenic risks (Figure 6), all the elements presented a value inside the safe interval. Among them, V and Mn were the metals with the highest percentage of soil screening level. With respect to the carcinogenic elements (Figure 7), Cd and Cr were included in the safe interval, while As levels exceeded clearly the regulatory limits. The reason could be the relative low levels marked by the US EPA as PRG for As, in comparison with the environmental concentrations of this element usually found. Nevertheless efforts should be focused on minimizing the release of As to the environment.

Table 4 presents the predicted oral exposure for adults and children living in residential areas near the HWI. Criteria for the calculations were previously reported (Nadal *et al.* 2004; US EPA 2004). Hazard Quotient for all metals was less than 1, which is considered the upper bound. Table 5 summarizes the predicted results for inhalation exposure of people living in the same area. In this case, a mean concentration of particulate matter in air of $71 \mu\text{g}/\text{m}^3$ was assumed (Departament de Medi Ambient 2002).

With respect to carcinogenic risks, only those elements for which a slope factor has been established were assessed: As ingestion, and As, Cd, and Cr inhalation. The risk of cancer was recalculated from the oral and the inhalation predicted exposures. Results are shown in Table 6. It can be noted that As ingestion would exceed the safe value of 10^{-6} , especially when assessing cancer risk in children. Some considerations should be noted: since the PRG used here corresponds to residential areas, this is the most conservative scenario. However, most samples were collected in rural zones. In addition, no age adjustment was carried out for calculations in children, overestimating the real value. Apart from As, only Cr inhalation could play a positive role in the potential increase in the number of cancers. The reason is that PRG for total chromium is established on the assumption that the ratio between Cr^{+6} and Cr^{+3} concentrations in soil is 1:6 (US EPA 2004). In the current study, no speciation was carried out. Therefore, this conservative calculation was taken into account.

Compared with metal levels found in recent years in a number of industrial areas (Morselli *et al.* 1993; Adamo *et al.* 2002; Sterckeman *et al.* 2002; Tuzen 2003; Yusuf *et al.* 2003), the current metal concentrations in the area under potential influence of the HWI are in the low part of these levels. Recently, Morselli *et al.* (2002) examined the impact of an Italian MSWI on the surrounding environment. Levels of heavy metals in soils and vegetation similar to those found near the

Table 4. Predicted oral exposure of metals for adults and children and hazard quotients

	RfD ₀ (mg kg ⁻¹ day ⁻¹)	Adults		Children	
		Predicted exposure (mg kg ⁻¹ day ⁻¹)	Hazard quotient	Predicted exposure (mg kg ⁻¹ day ⁻¹)	Hazard quotient
As	3.00E-04	6.10E-06	2.03E-02	1.14E-04	3.80E-01
Be	2.00E-03	4.00E-07	2.00E-04	7.47E-06	3.73E-03
Cd	5.00E-04	1.57E-07	3.14E-04	2.93E-06	5.87E-03
Cr ^a	3.00E-03	1.55E-05	5.15E-03	2.89E-04	9.62E-02
Hg	3.00E-04	5.71E-08	1.90E-04	1.07E-06	3.56E-03
Mn	2.40E-02	2.29E-04	9.54E-03	4.27E-03	1.78E-01
Ni	2.00E-02	2.13E-05	1.07E-03	3.98E-04	1.99E-02
Pb	3.50E-03	2.86E-05	8.18E-03	5.34E-04	1.53E-01
Sn	6.00E-01	1.36E-07	2.26E-07	2.53E-06	4.22E-06
Tl	6.60E-05	1.14E-07	1.73E-03	2.13E-06	3.23E-02
V	1.00E-03	2.09E-05	2.09E-02	3.90E-04	3.90E-01

^a Given as Cr⁶⁺

Table 5. Predicted exposure (mg kg⁻¹ day⁻¹) corresponding to metal inhalation by adults and children

	Adults	Children
As	8.66E-08	2.02E-07
Be	5.68E-09	1.33E-08
Cd	2.23E-09	5.21E-09
Cr	2.19E-07	5.12E-07
Hg	8.11E-10	1.89E-09
Mn	3.25E-06	7.59E-06
Ni	3.03E-07	7.07E-07
Pb	4.06E-07	9.48E-07
Sn	1.93E-09	4.50E-09
Tl	1.62E-09	3.79E-09
V	2.97E-07	6.92E-07

HWI assessed here were observed. On the other hand, the concentrations reported by a number of investigators in urban soils were higher than those found in the present study (Kaminski and Landsberger 2000; Mielke *et al.* 2001; Granero and Domingo 2002). The current values are even lower than those reported as background by Frink (1996).

In conclusion, the levels of metals found in soil and vegetation samples collected near the HWI do not show a continuous and homogeneous increase during the period 1998–2003 (approximately 5 years of regular operations). The fluctuations in the concentrations would suggest that the influence of the facility is minimal in relation to other metal pollution sources. Further studies should be focused on discovering the contribution of these sources to the global pollution of the area.

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References

Adamo P, Dudka S, Wilson MJ, Mchardy WJ (2002) Distribution of trace elements in soils from the Sudbury smelting area (Ontario, Canada). *Water Air Soil Pollut* 137:95–116

Table 6. Risk of cancer due to ingestion and inhalation of carcinogenic elements

		Adults		Children	
		SF _o /SF _i	Cancer risk	SF _o /SF _i	Cancer risk
Ingestion	As	1.5E+00	3.9E-06	1.5E+00	1.5E-05
Inhalation	As	1.5E+01	5.6E-07	6.5E+00	1.1E-07
	Cd	6.3E+00	6.0E-09	2.7E+00	1.2E-09
	Cr ^a	4.2E+01	4.0E-06	1.8E+01	7.9E-07

SF_o = Oral Slope Factor; SF_i = Inhalation Slope Factor.

^a Total chromium.

- Chang MB, Wu HT, Huang CK (2000) Evaluation on speciation and removal efficiencies of mercury from municipal solid waste incineration in Taiwan. *Sci Total Environ* 246:165–173
- Chang MB, Weng YM, Lee TY, Chen YW, Chang SH, Chi KH (2003) Sampling and analysis of ambient dioxins in northern Taiwan. *Chemosphere* 51:1103–1110
- Dempsey CR, Oppelt ET (1993) Incineration of hazardous waste: A critical review update. *Air Waste* 43:25–73
- Departament de Medi Ambient (2002) La qualitat de l'aire a Catalunya. Dades manuals i automàtiques, Període 2001–2002. Direcció General de Qualitat Ambiental. Departament de Medi Ambient, Generalitat de Catalunya, Barcelona, Spain
- Domingo JL, Schuhmacher M, Granero S, Llobet JM, de Kok HAM (1999) PCDD/F levels in the vicinity of an old municipal solid waste incinerator: Temporal variation in soils. *Arch Environ Contam Toxicol* 36:377–382
- Domingo JL, Schuhmacher M, Granero S, de Kok HAM (2001) Temporal variation of PCDD/PCDF levels in environmental samples collected near an old municipal waste incinerator. *Environ Monit Assess* 69:175–193
- Domingo JL (2002a) Public fear of dioxins from modern municipal waste incinerators is not justified. *Environ Health Perspect* 110:A288–A289
- Domingo JL (2002b) Human health risks of dioxins for populations living near modern municipal solid waste incinerators. *Rev Environ Health* 17:135–147
- Domingo JL, Agramunt MC, Nadal M, Schuhmacher M, Corbella J (2002c) Health risk assessment of PCDD/PCDF exposure for the population living in the vicinity of a municipal waste incinerator. *Arch Environ Contam Toxicol* 43:461–465
- Frink CR (1996) A perspective on metals in soils. *J Soil Contam* 5:329–359

- Granero S, Domingo JL (2002) Levels of metals in soils of Alcalá de Henares, Spain: Human health risks. *Environ Int* 28:159–164
- Hamer G (2003) Solid waste treatment and disposal: Effects on public health and environmental safety. *Biotechnol Adv* 22:71–79
- Hasselriis F, Licata A (1996) Analysis of heavy metal emission data from municipal waste combustion. *J Hazard Mat* 47:77–102
- Kaminski MD, Landsberger S (2000) Heavy metals in urban soils of East St. Louis, IL, Part I: Total concentration of heavy metals in soils. *J Air Waste Manage Assoc* 50:1667–1679
- Klumpp A, Klumpp G, Domingos M (1994) Plants as bioindicators of air pollution at the Serra do Mar near the industrial complex of Cubatao, Brazil. *Environ Pollut* 85:109–116
- Klumpp A, Hintemann T, Lima JS, Kandeler E (2003) Bioindication of air pollution effects near a copper smelter in Brazil using mango trees and soil microbiological properties. *Environ Pollut* 126:313–321
- Kuhn RG, Ballard KR (1998) Canadian innovations in siting hazardous waste management facilities. *Environ Manage* 22:533–545
- Lisk DJ (1988) Environmental implications of incineration of municipal solid waste and ash disposal. *Sci Total Environ* 74:39–66
- Llobet JM, Granero S, Schuhmacher M, Domingo JL (1999) Temporal variation in metal concentrations in soils and vegetation in the vicinity of a municipal solid waste incinerator. *Toxicol Environ Chem* 71:63–73
- Llobet JM, Schuhmacher M, Domingo JL (2000) Observations on metal trends in soil and vegetation samples collected in the vicinity of a hazardous waste incinerator under construction (1996–1998). *Toxicol Environ Chem* 77:119–129
- Llobet JM, Schuhmacher M, Domingo JL (2002) Spatial distribution and temporal variation of metals in the vicinity of a municipal solid waste incinerator after a modernization of the flue gas systems of the facility. *Sci Total Environ* 284:205–214
- Meneses M, Llobet JM, Granero S, Schuhmacher M, Domingo JL (1999) Monitoring metals in the vicinity of a municipal waste incinerator: Temporal variation in soils and vegetation. *Sci Total Environ* 226:157–164
- Mielke HW, Wang G, Gonzales OR, Le B, Quach VN, Mielke PW (2001) PAH and metal mixtures in New Orleans soils and sediments. *Sci Total Environ* 281:217–227
- Moraes RM, Klumpp A, Furlan CM, Klumpp G, Domingos M, Rinaldi MC, Modesto IF (2002) Tropical fruit trees as bioindicators of industrial pollution in southeast Brazil. *Environ Int* 28:367–374
- Morselli L, Zappoli S, Militerno S (1993) The presence and distribution of heavy metals in municipal waste incinerators. *Toxicol Environ Chem* 37:139–145
- Morselli L, Passarini F, Bartoli M (2002) The environmental fate of heavy metals arising from a MSW incineration plant. *Waste Manage* 22:875–881
- Mumma RO, Raupach DC, Sahadewan K, Manos CG, Rutzke M, Kuntz HT, Bache CA, Lisk DJ (1990) National survey of elements and radioactivity in municipal incinerator ashes. *Arch Environ Contam Toxicol* 19:399–404
- Nadal M, Schuhmacher M, Domingo JL (2004) Metal pollution of soils and vegetation in an area with petrochemical industry. *Sci Total Environ* 321:59–69
- Rumbold DG, Bruner MC, Mihalik MB, Marti EA (1997) Biomonitoring environmental contaminants near a municipal solid-waste combustor. *Environ Pollut* 96:99–105
- Schuhmacher M, Granero S, Bellés M, Llobet JM, Domingo JL (1996) Levels of metals in soils and vegetation in the vicinity of a municipal solid waste incinerator. *Toxicol Environ Chem* 56:119–132
- Schuhmacher M, Meneses M, Granero S, Llobet JM, Domingo JL (1997a) Trace element pollution of soils collected near a municipal solid waste incinerator: Human health risk. *Bull Environ Contam Toxicol* 59:861–867
- Schuhmacher M, Xifró A, Llobet JM, de Kok HAM, Domingo JL (1997b) PCDD/Fs in soil samples collected in the vicinity of a municipal solid waste incinerator: Human health risks. *Arch Environ Contam Toxicol* 33:239–246
- Schuhmacher M, Meneses M, Granero S, Llobet JM, Domingo JL (1998) Trace elements in vegetation grown near to an old municipal solid waste incinerator from Catalonia, Spain. *Fresenius Environ Bull* 7:42–50
- Schuhmacher M, Granero S, Rivera J, Müller L, Llobet JM, Domingo JL (2000) Atmospheric deposition of PCDD/Fs near an old municipal solid waste incinerator: Levels in soil and vegetation. *Chemosphere* 40:593–600
- Schuhmacher M, Agramunt MC, Rodriguez-Larena MC, Diaz-Ferrero J, Domingo JL (2002) Baseline levels of PCDD/Fs in soil and herbage samples collected in the vicinity of a new hazardous waste incinerator in Catalonia, Spain. *Chemosphere* 46:1343–1350
- Schuhmacher M, Agramunt MC, Bocio A, Domingo JL, de Kok HAM (2003) Annual variation in the levels of metals and PCDD/PCDFs in soil and herbage samples collected near a cement plant. *Environ Int* 29:415–421
- Sedman RM, Esparza JR (1991) Evaluation of the public health risks associated with semivolatile metal and dioxin emissions from hazardous waste incinerators. *Environ Health Perspect* 94:181–187
- Sterckeman T, Souay F, Proix N, Founder H, Perdrix E (2002) Assessment of the contamination of cultivated soils by eighteen trace elements around smelters in the North of France. *Water Air Soil Pollut* 135:179–194
- Thipse SS, Dreizin EL (2002) Metal partitioning in products of incineration of municipal solid waste. *Chemosphere* 46:837–849
- Tüzen M (2003) Determination of heavy metals in soil, mushroom and plant samples by atomic absorption spectrometry. *Microchem J* 74:289–297
- US EPA, Region 9 (2004) Preliminary Remediation Goals. Available at: <http://www.epa.gov/region09/waste/sfund/prg/index.htm>
- van Veizen D, Langenkamp H, Herb G (2002) Review: Mercury in waste incineration. *Waste Manage Res* 20:556–568
- Yusuf AA, Arowolo TA, Bamgbose O (2003) Cadmium, copper and nickel in vegetables from industrial and residential areas of Lagos City, Nigeria. *Food Chem Toxicol* 41:375–378