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Comparative Soil Metal Analyses in Sudbury (Ontario, Canada) and Lubumbashi (Katanga, DR-Congo)

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Abstract DR-Congo is a main world producer of copper (Cu) and cobalt (Co). Several hydrometallurgical plants and smelters also produced zinc, arsenic, and cadmium as by-products. In Sudbury (Canada), the production of nickel, copper and other metals has been maintained at high levels while industrial SO_2 emissions have been reduced by approximately 90% through combination of industrial technological developments and legislated controls. Metal analysis in the present study revealed that the levels of copper and cobalt in soils from mining sites in the Lubumbashi (DR-Congo) were up to 200 fold higher compared to contaminated Sudbury sites and tailings. Zinc content in soil samples from some mining areas in Lubumbashi was at least 70 times higher compared to samples from the Sudbury area. Nickel content in soil samples from Lubumbashi were much lower compared to the Sudbury Region samples. Overall, this study confirms that the African Copper belt region is among the ten most polluted areas in the world.

Keywords Soil metal content · DR-Congo · Sudbury · Lubumbashi · Mining · Pollution

Metal contamination is one of the most persistent and complex environmental issues, encompassing legacies of the past (e.g. abandoned mines) as well as impending, but poorly studied, threats (e.g. metallo-nanomaterials). The Sudbury region in Ontario, Canada has a history over the past 100 years of logging, mining and sulphide ore smelting, releasing more than 100 million tons of sulfur dioxide (SO_2) and tens of thousands of tons of cobalt, copper, nickel and iron ores into the atmosphere from the open roast beds (1888–1929) and smelters (1888–present) (Deng et al. 2007). The impact of this on the forests in the Sudbury region was extremely detrimental and the release of phytotoxic gases killed trees and ground flora over an extensive area (>1,000 km^2) (Hutchison and Symington 1997). Elevated concentrations of metal accumulations in soils and vegetations have been documented within short distances of the smelters in Sudbury compared to control sites (Freedman and Hutchinson 1980; Gratton et al. 2000; Nkongolo et al. 2007, 2008). During the last 30 years, production of nickel, copper and other metals has remained at high levels but industrial sulphur dioxide emission has been reduced by about 90%. This has allowed for a certain degree of recovery to occur (Backor and Fahselt 2004). This recovery has been sustained by the Sudbury Regreening/Land Reclamation program that has reached over 9 million trees planted in the Greater Sudbury Region.

Like in Sudbury, the mining industry in Katanga specifically in the Greater Lubumbashi was initiated in early 1900s. Copper and Cobalt were in several hydrometallurgical plants and smelters, which also produced zinc, arsenic, and cadmium as by-products (Prasad 1989). DR-Congo is a main producer of Copper and Cobalt with 6% and 40% of world production, respectively in 1980. Two mining sites have been very prominent in the Greater Lubumbashi including Etoile and Penga Penga mines. There are open pits and underground mines with washing plants and concentrators generating large mine tailings. Little research has been conducted on metal pollution. Neither historical nor actual data on environmental contamination by metals are available for the Greater Lubumbashi (DR-Congo) (Banza et al. 2009).

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The main objective of the present study is to compare the current level of metal content in soil collected from natural and reclaimed stands from the Greater Sudbury region and from two main mining sites in Greater Lubumbashi (DR-Congo).

Materials and Methods

Soil samples were collected from five sites within the Sudbury region (site 1–5) (Fig. 1). One site located approximately 90 km from Sudbury was used as a reference (site 5). For each area, ten soil samples were collected. Soil samples were collected from top soil 0–5 cm (organic layer) and from bottom soil 5–20 cm (mineral layer). These samples were air dried, labeled, and stored prior to analysis. In DR-Congo, soil samples were collected from four sites including two abandoned mining areas at Penga Penga and Etoile mines in Lubumbashi, and two control sites located at 50 and 500 km from the mining sites (Fig. 2). Since the organic layer was very thin, five samples were collected from each site from top to 5 cm depth.

Soil samples were analyzed in collaboration with TESTMARK Laboratories Ltd. Sudbury, Canada. The laboratory is ISO/IEC 17025 certified, a member of the Canadian Council of Independent Laboratory (CCIL) and the Canadian Association of Environmental Analytical Laboratories (CAEAL), and is accredited by the Standards Council of Canada (SSC). The laboratory employs standard QA/QC procedures, involving blank and replicate analyses and with recovery rate of 98% ± 5% in analyses of spiked samples depending on element selected, in their inductively coupled plasma mass spectrometry (ICPMS) analyses reported here. The minimum detection limits (MDL) following microwave digestion of plant tissue Aqua Regia for elements reported here, were: Aluminum 0.05 µg g (0.5 µg/g), Arsenic 0.05 µg/g (0.5 µg/g), Cadmium 0.05 µg/g (0.5 µg/g), Cobalt 0.05 µg/g (0.5 µg/g), Copper 0.05 µg/g (0.5 µg/g), Iron 1.0 µg/g (10 µg/g), Lead 0.05 µg/g (0.5 µg/g), Magnesium 0.2 µg/g (2.0 µg/g), Manganese 0.05 µg/g (0.5 µg/g), Nickel 0.05 µg/g (0.5 µg/g) and Zinc 0.05 µg/g (0.5 µg/g). These MDLs reflect actual sample weights and dilutions; instrument detection limits were lower.

The data for the metal levels in soil were analyzed using SPSS 7.5 for Windows. All the data were transformed using a $\log_{10}$ transformation to achieve a normal distribution. ANOVA followed by Tukey's HSD multiple comparison analysis were performed to determine significant differences ($p < 0.05$) among the sites.

Results and Discussion

Recovery and precision for all elements in reference soil samples were within acceptable range. The estimated levels of metal content in different sites from the Greater Sudbury Region in Canada are illustrated in Table 1. The levels of the metals measured were low in the control sites. Overall, the results indicated that nickel and copper continue to be the main contaminants of top soil (Table 1) in sites near the smelters (site 1 and 2). The values ranged from 30.9 to 1,600.0 mg kg^{-1} and from 52.3 to 1,330.3 mg kg^{-1} for nickel and copper respectively (Table 1). Arsenic concentration exceeded the OMEE (Ontario Ministry of Environment and Energy) guidelines in site 1 and manganese level exceeded the guideline in site 2. Their concentration ranged from 2.2 to 46.0 mg kg^{-1} and 163.6 to 6,610.3 mg kg^{-1} for arsenic and manganese, respectively (Table 1).

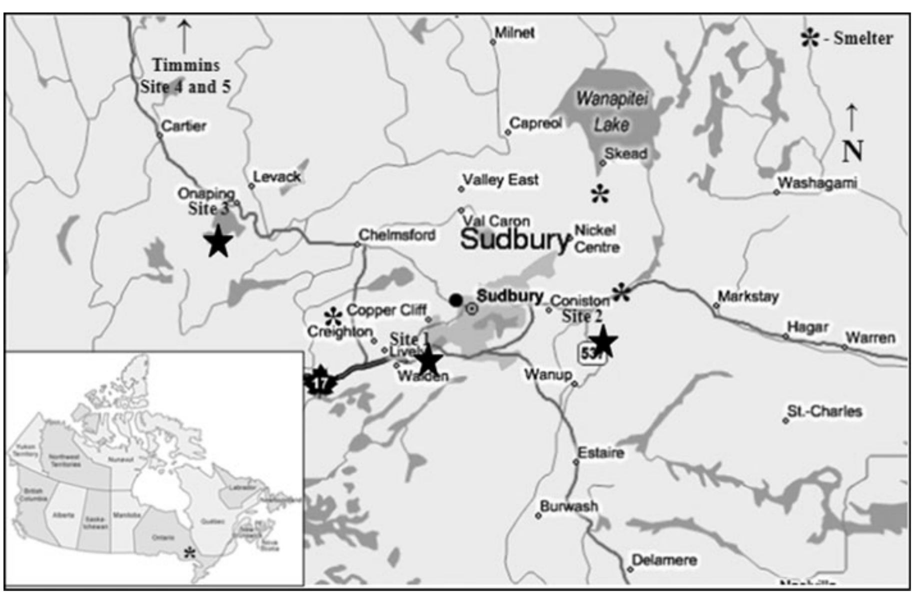

Fig. 1 Locations of the soil sampling areas from the Greater Sudbury Region. Site 1: Lively; Site 2: Coniston (close to HW17); Site 3: ≈40 km from Sudbury HW144 towards Timmins; Site 4: ≈16 km from site 3 HW144 towards Timmins; Site 5 (control): ≈35 km from Site 4 HW144 towards Timmins

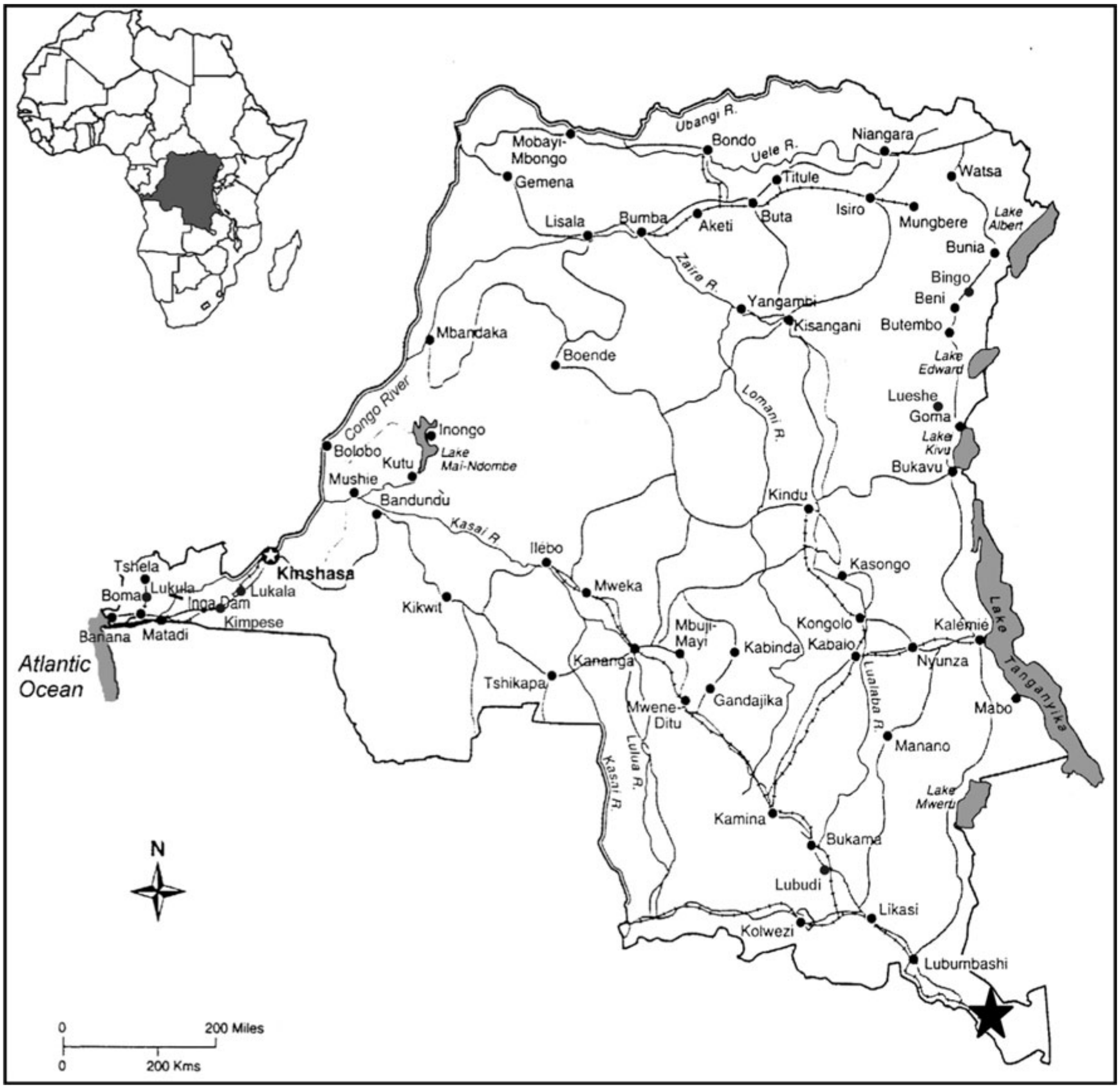

Fig. 2 Locations of the soil sampling area from the DR-Congo region. Soil samples were obtained from the Lubumbashi area (Penga Penga, Etiole and Control 1) and one soil sample was obtained from Gandajika area (Control 2)

Table 1 Metal concentrations in top layer (0–5 cm) of soil from the Sudbury region sites, concentrations are in mg kg^{-1}, dry weight

Sampling sites	Elements											pH
	Aluminum	Arsenic	Cadmium	Cobalt	Copper	Iron	Lead	Magnesium	Manganese	Nickel	Zinc	
Site 1	7,360b	46b	2b	29b	1,330bc	31,433bc	176bc	2,970b	163a	1,600b	86bc	4.6
Site 2	9,193b	10a	1b	37b	373ac	12,933ac	46ac	6,866b	6,610c	318bc	52ab	4.5
Site 3	7,670b	10a	0.9b	22a	170a	6,476a	39ac	2,706b	539b	120bd	60ac	–
Site 4	7,090b	2a	0.3a	6a	52a	10,233ac	18a	2,996b	165a	54acd	32a	4.0
Site 5 (control)	1,673a	2a	0.7b	2a	93a	2,913a	88ab	349a	206a	30acd	55a	3.8
Tailings	–	–	0.3a	34b	300ac	–	46ac	–	–	292bc	59ac	–

Means in columns with a common alphabets are not significantly different based on Tukey multiple comparison test ($p \geq 0.05$). Site 1: Lively; Site 2: Coniston (close to HW17); Site 3: ≈40 km from Sudbury HW144 towards Timmins; Site 4: ≈16 km from site 3 HW144 towards Timmins; Site 5 (control): ≈35 km from Site 4 HW144 towards Timmins. Tailings data represent means of two tailings located near smelters

Aluminum, iron and magnesium concentrations were significantly higher in sites 1 to 4 (top layer, Table 1) compared to the control site 5. The values ranged from 1,673.3 to 9,193.3 mg kg^{-1}, 2,193.3 to 31,433.3 mg kg^{-1} and 349.6 to 6,866.6 mg kg^{-1} for aluminum, iron and magnesium, respectively (Table 1). Cadmium, cobalt, lead and zinc levels were within the OMEE guideline. The values for these metals ranged from 0.3 to 2.1 mg kg^{-1}, 1.6 to 37.9 mg kg^{-1}, 18.2 to 176.0 mg kg^{-1} and 52.0 to 86.8 mg kg^{-1} (Table 1). The control site 5 was always among the least contaminated for the metals analyzed. All the metal concentrations obtained from the bottom layer (5–20 cm) were within the OMEE guideline (data not shown). Surprisingly, the data from tailings were similar or significantly lower than other contaminated sites.

Soil analysis of samples from the Penga Penga and Etoile (Table 2) abandoned mining areas in Greater Lubumbashi revealed a level of copper that was 10–14 times higher than the most contaminated site from the Sudbury Region. These values were 200 folds the limits of OMEE guidelines for copper. Copper content in samples from the control site located 50 km from the mining sites were significantly lower than that observed in mining areas and similar to the levels detected in contaminated sites from the Sudbury Region. The analysis of soil samples from the control site located 700 km from the mining areas in DR-Congo revealed only a background level of copper much below the OMEE guideline limit for copper.

The level of cobalt observed in Etoile mining area was 20 fold higher than in samples from Penga Penga site in Lubumbashi (Table 2). These values were 200 fold higher than the contaminated sites from the Greater Sudbury Region in Canada. The levels of cobalt in samples from control sites in DR-Congo were significantly lower than Etoile and Penga Penga mining sites, but similar or higher than the levels detected in contaminated sites from the Sudbury Region. These values were lower than the OMEE guideline limit for cobalt of 50 mg kg^{-1}.

The zinc content in soil from Penga Penga (1,250 mg kg^{-1}) was seven fold higher than samples from Etoile mining area (Table 2). This value was at least 70 times higher than the zinc content detected in samples from contaminated sites from the Sudbury area. It should be noted that the zinc content in samples from the Etoile mining area was within the OMEE guideline limit. The level of arsenic was fivefold higher in Penga Penga (101 mg kg^{-1}) compared to Etoile mining site in the Greater Lubumbashi (Table 2). These values were twice the arsenic content found in site 1 (most contaminated area) from the Greater Sudbury Region.

As expected, the nickel content from samples from the mining areas and control sites in Greater Lubumbashi were much lower compared to nickel content in soil samples from the Greater Sudbury Region. In fact, the levels of nickels in samples from Penga Penga, Etoile, control 1 and Control 2 were 6,33.5,4.8 and 12.3 mg kg^{-1}, respectively. The nickel level in samples from the Greater Sudbury Region (Canada) were 1,600,318,120,54 and 30 mg kg^{-1}, for sites 1, 2, 3, and 4, respectively.

The levels of aluminum and iron were extremely high in soil samples from Lubumbashi (DR-Congo) even in the control site located 500 km from the mining areas (Table 2). In fact the aluminum and iron content in soil from control site 2 located 500 km from the mining areas in DR-Congo were twice to three fold higher compared to mining sites.

The Canadian Environmental Protection Act (CEPA) has labeled mercury, inorganic arsenic, cadmium, oxidic, sulphidic, soluble inorganic nickel compounds, and a number of other substances to be toxic. There are 15 base metal smelters in Canada emitting CEPA substances at various levels. Of these 15, five are in Ontario with the major concentration of activity being in the Sudbury district where Vale (formerly Inco) and Xstrata Nickel (formerly Falconbridge) have operated for years (Dudka et al. 1995). The 2001 soil survey analyzed over 10,000 samples

Table 2 Metal concentrations in soil from the DR - Congo, concentrations are in mg kg^{-1}, dry weight

Sampling sites	Elements											pH
	Aluminum	Arsenic	Cadmium	Cobalt	Copper	Iron	Lead	Magnesium	Manganese	Nickel	Zinc	
Penga Penga (Lubumbashi)	7,480	101	19.8	204	11,600	20,200	809	348	94.4	6.0	1,250	6.1
Etoile (Lubumbashi)	9,270	20	0.9	6150	14,200	29,300	21	1,880	3,300	33.5	178	7.1
Control 1 (Lubumbashi)	12,200	4.1	1.7	17.4	281	21,400	38.9	372	325	4.8	69.2	6.1
Control 2 (Gandajika –Kasai)	16,500	3.8	0.1	33.4	28	62,100	27.8	264	1,280	12.3	69	5.3
LSD	1,830	12	1.4	58.0	395	10,700	35	180	381	9.2	89	–

from hundreds locations within the Sudbury area. The highest levels of nickel, copper, lead, cobalt and arsenic were found around the three industrial centers of Copper Cliff, Coniston, and Falconbridge. These current findings are consistent with historical ministry results. The highest metal concentrations were found in the upper soil layers, indicating air emissions as the source.

The mining cities of Lubumbashi and Sudbury present contrasting context. In both cities pits and underground mines were developed with washing plants and concentrators. In Lubumbashi, artisanal and semi-clandestine miners have been intensively exploiting and smuggling Copper and Cobalt secondary ores in surface deposits. Metal surfaces have been built with little regard for environmental issues (Banza et al. 2009). There are no land reclamation programs and environment degradations from past mining activities have not been addressed.

In Sudbury (Canada) on the other hand during the last 25 years, production of nickel, copper and other metals has been maintained at high levels while industrial sulphur dioxide (SO_2) emissions have been reduced by approximately 90% through combination of industrial technological developments and legislated controls. This has allowed for some degree of recovery to occur such as improved air quality and natural recovery of damaged ecosystems during this period of reduced emissions at Sudbury. The recovery has been further done through the reforestation program by planting over 9 million trees such as conifers in the Sudbury region.

In DR-Congo, the most recent study by Banza et al. (2009) reveals a substantial exposure to several metals, especially in children in Lubumbashi and other mining areas in the Katanga province. The urinary cobalt concentrations found in population from Greater Lubumbashi are the highest ever reported for a general population (Banza et al. 2009). In fact, the African Copper belt, on the border between Zambian and DR-Congo, are among the ten most polluted areas worldwide (Audry et al. 2004; The Blacksmith institute 2008; Banza et al. 2009) based from Zambia mining areas (Tembo et al. 2006). The present study represents the first pollution data for Katanga. This study reveals that the environmental contamination is even larger in Lubumbashi (Katanga) compared to Kabwe in Zambia.

Mining districts are characterized by naturally occurring metals in soil, sediment, rock, and water at concentrations that could result in their classification as "contaminated sites" (Painter et al. 1994). The usually high concentrations of iron in Sudbury sites and Lubumbashi even in control sites appear to be the result of naturally occurring iron. This is also true for aluminum and manganese in Congolese sites. The soil type and composition plays an important role for heavy metal retention. In general, coarse-grained soils exhibit lower tendency for heavy metal adsorption than fine grained soils. Soil pH is the most important parameter influencing metal-solution and soil-surface chemistry. In general, heavy metal adsorption is small at low pH values. Adsorption then increases at intermediate pH from near zero to near complete adsorption over a relatively small pH range (Bradl 2004). In fact, in the present study, the pH values were low (<4) in the Sudbury areas and intermediates (ranging from 5.7 to 7) in targeted areas in DR-Congo.

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References

Audry S, Schafer J, Blanc G, Jouanneau JM (2004) Fifty-year sedimentary record of heavy metal pollution (cd, Zn, Cu, Pb) in the Lot River reservoir (France). Environ Pollut 132:413–426

Backor M, Fahselt D (2004) Physiological attributes of the lichen *Cladonia pleurota* in heavy metal-rich and control sites near Sudbury (Ontario, Canada). Environ Exp Bot 52:149–159

Banza CLN, Nawrot TS, Haufroid V, Decree S, De Putter T, Smolders E, Kabyla BI, Luboya ON, Ilunga AN et al (2009) High human exposure to cobalt and other metals in Katanga, a mining area of the Democratic Republic of Congo. Environ Res 1009:745–752

Bradl HB (2004) Adsorption of heavy metal ions on soils and soils constituents. J Colloid Interface Sci 277:1–18

Deng J, Liao B, Ye M, Deng D, Lan C, Shu W (2007) The effect of heavy metal pollution on the genetic diversity in zinc/cadmium hyperaccumulator *Sedum alfredii* populations. Plant Soil 297:83–92

Dudka S, Ponce-Hernandez R, Hutchinson TC (1995) Current level of total element concentrations in the surface layer of Sudbury's soils. Sci Total Environ 162(2–3):161–171

Freedman B, Hutchinson TC (1980) Pollutant inputs from the atmosphere and accumulations in soils and vegetation near a nickel-copper smelter at Sudbury, Ontario, Canada. Can J Bot 58:108–132

Gratton WS, Nkongolo KK, Spiers GA (2000) Heavy metal accumulation in soil and jack pine (*Pinus banksiana*) needles in Sudbury, Ontario, Canada. Bull Environ Contam Toxicol 64(4):550–557

Hutchison TC, Symington MS (1997) Persistence of metal stress in a forested ecosystem near Sudbury, 66 years after closure of the O'Donnell roast bed. J Geochem Explor 58:323–330

Nkongolo KK, Mehes M, Deck A, Michael P (2007) Metal content in soil and genetic variation in *Deschampsia cespitosa* populations from Northern Ontario (Canada): application of ISSR markers. Eur J Genet Toxicol (March issue):1–38. www.Swan.ac.uk/get/ejgt/Nkongolo

Nkongolo KK, Vaillancourt A, Dobrzeniecka S, Mehes M, Beckett P (2008) Metal content in soil and black spruce (*Picea mariana*) trees in the Sudbury region (Ontario, Canada): Low concentration of arsenic, cadmium, and nickel detected near smelter sources. Bull Environ Contam Toxicol 80(2):107–111

Painter S, Cameron EM, Allan R, Rouse J (1994) Reconnaissance geochemistry and its environmental relevance. J Geochem Explor 51(3):213–246

Prasad MS (1989) Production of copper and cobalt at Gecamines, Zaire. Miner Eng 2:521–541

Tembo BD, Sichilongo K, Cernak J (2006) Distribution of copper, lead, cadmium and zinc concentrations in soils around Kabwe town in Zambia. Chemosphere 63:497–501

The Blacksmith Institute (2008). World's Most Polluted Places 2007. www.blacksmithinstitute.org (accessed 2008)