4.0 Distribution of Chemicals of Concern in the Study Area

Authors

Graeme A. Spiers, PhD
MIRARCO, Laurentian University
935 Ramsey Lake Road, Sudbury, ON Canada P3E 2C6
Email: gspiers@mirarco.org

Christopher D. Wren, PhD
MIRARCO, Laurentian University
935 Ramsey Lake Road, Sudbury, ON Canada P3E 2C6
Email: cwren@mirarco.org

Dave McLaughlin
Ontario Ministry of the Environment
125 Resources Road, Toronto, ON Canada M9P 3V6
Email: dave.l.mclaughlin@ontario.ca

Table of Contents

Tables

Figures

4.1 Sudbury Geology and Soils

4.1.1 Geology

Metals constitute a natural component of soils, with concentrations dependent on soil mineral composition and geochemical history. Localized, strongly elevated metal concentrations have been created in surface soils by atmospheric deposition in the neighborhood of metal extraction facilities. Soils, more than any other sampling medium, reflect the total historical metal accumulation from the point source, but modified to varying degrees by soil-forming processes and erosion. The metals originating from anthropogenic sources in a soil do not behave differently from the naturally present metal ions.

The Sudbury Geological Structure is an elliptical unit produced by a meteorite colliding with the southern part of the Superior Province (see Figure 2.1). The melted rocks form the world's largest impact-related melt sheet. The melt sheet of the Sudbury Igneous Complex is composed, from base to top, of norite, quartz gabbro and granophyre. As host to the ore deposits, its mineralogy and geochemistry are important in discriminating between anthropogenic contamination and influences of bedrock in the geochemistry of soils. The Sudbury Igneous Complex has been divided into the Main Mass (norite, quartz gabbro, and granophyre) and Sublayer (Contact Sublayer and Offset Sublayer) (Dressler et al. 1991). Mineralization of importance occurs in the Sublayer and the Offset dikes.

4.1.2 Physiography

The Sudbury area includes parts of the Abitibi Uplands, Penokean Hills and Cobalt Plain of the James Physiographic Region and a small part of the Laurentian Highlands within the Laurentian Physiographic Region (Barnett and Bajc 2002). The Abitibi Uplands north of Sudbury are underlain by Archean crystalline rocks and comprise broad, rolling, bedrock-controlled surfaces rising gently toward the Abitibi Uplands southern boundary to a maximum elevation of 450 m. Locally, relief may be as much as 90 m along deeply incised canyons (Dredge and Cowan 1989). The Laurentian Highlands is an old erosion surface consisting of low, rounded knobs and ridges; locally, relief may be as much as 30 to 50 m. Elevation of this area is up to 300 m (Barnett and Bajc 2002).

The Sudbury Basin consists of an oval central low, the 'Valley', rimmed by a zone of high relief ridges to the north, east and south. The rocks of the Sudbury Igneous Complex and the Onaping Formation form these ridges. The Valley is a plain exhibiting low relief interrupted by bedrock ridges caused by the broad folding of the Chelmsford Formation. The plain slopes to the south-west with a drop in elevation of about 40 m over 39 km (Barnett and Bajc 2002). Local relief in the Valley is about 15 m and in places as much as 30 m. Some bedrock ridges reach 320 m above sea level.

4.1.3 Soils

The characteristics of soil are greatly influenced by the nature of the parent material, together with weathering and erosion processes. The soil mineralogical and chemical composition in the Sudbury area will, therefore, reflect the bedrock geology of the region, the up-ice geology, the organic input from the flora and fauna of the region, and exogenous materials such as particulate matter from both long- and short-range transport processes. Sudbury area soils belong to five orders of the Canadian Soil Classification System (Agriculture Canada Expert Committee on Soi1 Survey 1987): Luvisolic, Gleysolic, Podzolic, Brunisolic, and Organic (Gillespie et al. 1983).

The focus of this study was on well-to-imperfectly drained soils developed on the regional glaciogenic sediments. Since the surface peat soils are only fed by atmospheric sources, these organic soils are excellent archives of historical aerosolic inputs (Zoltai 1988; Shotyk et al. 2000, 2001, 2002).The well-to-imperfectly drained undisturbed soils of the Sudbury region are characterized by having organic (LFH) horizons ranging in thickness from 2 to 15 cm. The designation LFH refers to the fresh plant detritus (L=litter) on the soil surface, the partially decomposed organic layer (F=fermentation) and the well-decomposed organic layer (H=humus). These poorly studied LFH horizons, initially composed almost entirely of organic matter, are crucial sinks for the aerosolic particles (Spiers et al. 2002) from both local and long-range sources, acting both as filters to prevent particle translocation to lower horizons, and as exchange surfaces to absorb dissolved metals in precipitation and water through flow. Colloidal soil organic matter, for example, strongly adsorbs Cu, Zn, Fe and other transition metal ions, by acting as a chelating agent (Bohn et al. 2001).

In a study in the Falconbridge area, Golder Associates Ltd. (2001) reported total C content ranges from a low of 0.16% to a peak of 10.1% in the 0–5 cm layer of the sampled soils. The study documented carbonate content ranging from below detection limit to a high of 0.89% in the same 0–5 cm layer, with the higher levels being in areas which were either landscaped or limed. Gundermann and Hutchinson (1995) reported that the organic C content of soils in the 0–5 cm layer in the Coniston smelter area decreased over the period between 1972 and 1992, probably because of soil erosion. The latter study also reported a concomitant decrease in water extractable metal content from 74, 33 and 52 mg/kg Ni, Cu, and Al to 2, 2, and 3 mg/kg, Ni, Cu and Al, respectively, suggesting that the decrease is strongly linked to the erosion of surface organic matter. Hazlett et al. (1983) reported organic C content of soils around the Coniston smelter in the range 0.1% to 19.4%, with the high values being for the LFH horizons and the lowest values for C horizons. A study of soil samples collected for the 0–20 cm layer from throughout the Sudbury region some 12 years ago, documented organic carbon content ranging from about 0.5% to 2.1% (Adamo et al. 2002).

4.2 Regional Distribution of Metals in Sudbury Soils

4.2.1 Metal Distribution in Parent Materials

The sites selected for the regional study were sampled to a depth of greater than 80 cm, wherever possible, using bucket augurs to obtain soil samples assumed to be unaffected by recent industrial activities. These samples, referred to as parent material samples, were obtained from over 70% ($n = 254$) of the sites visited during the sampling program. The analytical data obtained from these samples represent the first known attempt to establish the pre-industrial levels of metals in regional soils, with the data providing an excellent indication of regional background levels of *Aqua Regia* extractable metal(loid)s.

The concentrations of soil parameters measured in the parent material are presented in Table 4.1. Also presented in Table 4.1 for comparison purposes are mean values for soils of the Canadian Shield from an earlier study (McKeague et al. 1979) and Ontario Ministry of the Environment (MOE) Table F values, which are considered to represent Ontario background soil concentrations.

The soils in the Sudbury region are formed on primarily coarse textured tills and glacio-fluvial materials which are mineralogically dominated by quartz and feldspars, with minor amounts of heavy and clay minerals. As the heavy and clay mineral fraction are the sources for the metals of interest to the current studies, it is not surprising to observe that both the mean concentration and 95th percentile of most elements measured in the parent material are less than the generic Ontario background level (Table F values). The Table F criteria in the MOE *Guideline* reflect the mean plus two standard deviations of the entire provincial background soil data base, which is approximately the 97.5th percentile. Therefore, if the Sudbury Regional soil survey data are normally distributed, the mean concentrations should be less than the MOE generic background levels. In fact, the only two elements of the Sudbury regional sampling that have 95th percentile values greater than Table F are Cr and Ni, perhaps reflecting some incorporation of local metal-rich bedrock in the glacial detritus of the soil parent materials.

Table 4.1 **Summary of the Concentration of Major and Trace Elements in Parent Soil Materials ($n = 254$)**

Parameter	Arithmetic mean	Range	95th UCL	Standard error	Standard deviation	Shield soils[1]	MOE Table F[2]
Al (%)	1.78	0.21–9.1	1.9	0.067	1.07	6.7	NG
Ca (%)	0.78	0.1–5.8	0.8	0.067	1.11	1.8	NG
Fe (%)	2.27	0.21–7.8	2.4	0.068	1.09	2.5	NG
Mg (%)	0.67	0.04–3.8	0.7	0.034	0.54	0.53	NG
As (mg/kg)	1.11	<dl–98	4.1	n/a	6.5	n/a	17
Ba (mg/kg)	98.4	13–390	120	n/a	80.5	n/a	NG
Be (mg/kg)	0.15	<dl–1.1	0.4	n/a	0.2	n/a	NG
Cd (mg/kg)	<dl	<dl	<dl	n/a	n/a	n/a	1

Parameter	Arithmetic mean	Range	95th UCL	Standard error	Standard deviation	Shield soils[1]	MOE Table F[2]
Cr (mg/kg)	56.4	12–130	59.1	1.63	26.04	19	71
Co (mg/kg)	8.9	2–38	9.5	0.29	4.64	19	21
Cu (mg/kg)	26.4	<dl–270	28.8	1.73	27.65	12	85
Mn (mg/kg)	293	23–1800	342	11.35	180.8	417	NG
Mo (mg/kg)	0.11	<dl–3.1	0.8	0.03	0.46	n/a	2.5
Ni (mg/kg)	36.1	8.5–163	41.9	1.32	21.0	12	43
Pb (mg/kg)	5.9	1–47	7	0.24	3.85	20	120
Se (mg/kg)	0.06	<dl–2	0.06	0.02	0.31	0.18	1.9
Sr (mg/kg)	43.8	11–80	45.7	1.08	17.27	n/a	NG
V (mg/kg)	43.3	6.7–220	47.4	1.29	20.61	n/a	91
Zn (mg/kg)	29.7	5.4–160	31.9	1.16	18.5	57	160
pH (n = 35)	5.6	3.7–7.8	NC	0.15	0.9	n/a	n/a

Based on values for 254 samples; pH reported for subset of 35 samples (CEM 2004).

UCL = upper confidence level.

NG = no guideline available.

NC = not calculated.

n/a = not available.

<dl = below detection limit.

[1] Values for soils of the Canadian Shield (McKeague et al. 1979).

[2] Table F considered Ontario background concentrations (MOE 1997).

Although the bedrock in the Sudbury basin is known to be locally highly mineralized, this is not reflected in higher background soil concentrations relative to the Ontario generic criteria, possibly because of dilution with upstream rock materials due to glaciations. Furthermore, the base metal-rich mineral phases hosted in the sulfide-rich units of the regional bedrocks are relatively soft, and may thus have been transferred and dissolved from the surficial materials as a result of glacial activity and weathering. In fact, the true natural 'background' surface soil metal concentrations in the mineralized areas of the Sudbury basin are similar to those documented in other regions of the Canadian Shield region. The results of the parent material analysis and comparison with Table F indicate that background metal concentrations in the Sudbury area are not higher than levels considered as background for other parts of Ontario. This is an interesting conclusion because the MOE specifically avoided the Sudbury basin area when collecting the samples that were used to calculate the 1997 Table F background-based soil guidelines because of the suspicion that the surficial soils may be mineralized above normal background levels.

In the following discussion, the values obtained for Sudbury parent soils are compared with data for parent materials from a variety of sources, including 'background' Ontario soil concentrations.

4.2.1.1 Arsenic

The maximum value for As in the parent samples was 98 mg/kg, with minimum values below detection limits. The arithmetic mean concentration of As in the parent materials of the Sudbury region was 1.1 mg/kg. Of the 254 parent material samples analyzed, only 24 had an As concentration above detection limits by the methodology used in this study. The MOE Table F background concentration limit for As (17 mg/kg) for all non-agricultural use for surface materials was exceeded in six samples, centered on the Copper Cliff smelter. Since the Table F guideline is essentially the 98th percentile, if the sample population is normally distributed, about two out of every 100 samples may have a concentration greater than Table F. Therefore, for a population size of 254 samples, one would expect about five samples to exceed the normal background range, which is close to what was observed. Although comparative data for the levels of As for a similar study in Shield soil materials is not available, mean levels for uncontaminated soils of Southern Ontario are documented at 5.2 mg/kg, while that for U.S. soils is 7.4 mg/kg, with a range from 1 to 97 mg/kg (Shacklette et al. 1971; Gough et al. 1988). For comparison, Henderson et al. (2002) estimated the background level of As for soils of the Rouyn-Noranda area approximately 250 km north-east of Sudbury at 6 mg/kg. In a study of background concentrations for soils formed in tills underlain by Precambrian bedrock formations in the Flin Flon region of Manitoba, McMartin et al. (1999) documented As mean concentration as 20 mg/kg.

4.2.1.2 Cadmium

Cadmium was below the method detection limit (MDL) for the 254 samples of regional soil parent materials. Henderson et al. (2002) estimated the background level of Cd for soils of the Rouyn-Noranda area at 1 mg/kg, a level in contrast to a measured mean background concentration of 0.3 mg/kg for soils formed in tills in the Flin Flon region of Manitoba (McMartin et al. 1999).

4.2.1.3 Cobalt

With a range in concentration from 2 to 38 mg/kg, the arithmetic mean Co level (8.9 mg/kg) in soil parent materials of the Sudbury region was lower than those described by McKeague et al. (1979) for Shield soils. However, the mean value is similar to that defined for U.S. soils (10 mg/kg) by Shacklette et al. (1971) and Gough et al. (1988). Several sample sites in the Sudbury area had concentrations above the MOE Table F background Co guideline of 21 mg/kg for all non-agricultural uses for surface materials.

4.2.1.4 Copper

The overall mean level of Cu (26.4 mg/kg) was similar to that defined for U.S. soils (25 mg/kg) by Shacklette et al. (1971) and Gough et al. (1988), but double that documented by McKeague et al. (1979) for samples of Shield soils. One site in the Kelley Lake delta, with a Cu level of 270 mg/kg, skewed the data for the regional distribution of Cu. This site is probably enriched with Cu as a result of erosion from the mining and smelter operations further up the Junction Creek watershed. This is also the only site in the region with soil Cu levels above the MOE Table F guideline (85 mg/kg) for surface materials. Interestingly, the data obtained in the current Sudbury study were similar to the estimation of background concentration of Cu at 30 mg/kg for soil of the Rouyn-Noranda area approximately 250 km north-east of Sudbury (Henderson et al. 2002). The measured mean background concentration of Cu in soils formed in tills in the Flin Flon region of Manitoba was 122 mg/kg (McMartin et al. 1999).

4.2.1.5 Lead

The mean regional value for Pb (5.9 mg/kg) in Sudbury area soil parent materials was much below that documented by Dudas and Pawluk (1980) for Prairie soils, by McKeague et al. (1979) for soils of the Shield region and by Shacklette et al. (1971) and Gough et al. (1988) for soil forming materials of the conterminous U.S. (20 mg/kg). The Pb levels for all parent material sample sites in this Sudbury area study had concentrations below the MOE Table F background lead concentration limit of 120 mg/kg for all non-agricultural uses for surface materials. The Table F soil Pb guideline is considerably higher than most of the parent material soil Pb data because the MOE guideline is calculated from samples of surface soil. Although known industrial point sources of contaminants were obviously avoided during the background sampling, the ubiquitous use of leaded gasoline for seven decades in the 1900s resulted in the widespread distribution of Pb in the Ontario airshed, and subsequently deposition of Pb to surface soil. Therefore, the background soil Pb guideline for Ontario reflects a significant societal anthropogenic signal. Furthermore, the data obtained in the current Sudbury study are much lower than the estimate of background concentration of Pb at 80 mg/kg for soil of the Rouyn-Noranda area approximately 250 km north-east of Sudbury (Henderson et al. 2002). The measured mean background concentration of Pb in soils in the Flin Flon region of Manitoba was 8 mg/kg (McMartin et al. 1999).

4.2.1.6 Nickel

The arithmetic Ni level (36 mg/kg) for the Sudbury region was higher than those levels documented in the review by McKeague et al. (1979) for agricultural soils of the Shield (12 mg/kg) and in conterminous U.S. soils (20 mg/kg) (Shacklette et al. 1971; Gough et al. 1988). The range in parent material Ni concentrations was from 9 to 163 mg/kg, with the higher concentrations being in the soil parent materials near the Kelly Lake delta that is the receiver of the sediment load from the major mineral extraction operations of the region. The high values were, however, below the MOE Table F guideline of 43 mg/kg for surface materials where soil pH is 5.0 to 11.0. The measured mean background concentration of Ni in soils formed in tills in the Flin Flon region of Manitoba was 67 mg/kg (McMartin et al. 1999), approximately twice as high as in the soils of the Sudbury region. The data obtained in the current Sudbury study were much lower than the estimation of background concentration of Ni at 1 mg/kg for the humus layer of soils of the Rouyn-Noranda area approximately 15 km north-east of Sudbury (Henderson et al. 2002).

4.2.1.7 Selenium

The arithmetic Se level (0.06 mg/kg) for the Sudbury region was lower than documented in the review by McKeague et al. (1979) for agricultural soils of the Shield (0.18 mg/kg). The reports of Shacklette et al. (1971) and Gough et al. (1988) for soils of the U.S. did not document levels for Se. The values reported in this study were considerably below the MOE Table F guideline of 1.9 mg/kg for surface materials where soil pH is 5.0 to 11.0.

4.2.2 Regional Distribution of COC in Surface Soils

A primary objective of the regional soil survey was to measure the spatial distribution (geographic area) of metals in surface (0 to 5 cm) soils to determine the potential 'footprint' of particulate airborne emissions from the Sudbury smelters. The analytical methods and detection limits for the 2001 Soils Study are described in Chapter 3. A summary of metal concentrations in regional surface soils (0–5 cm layer) is provided in Table 4.2 with further discussion below. Data from other studies and other smelter locations are provided for comparison with the Sudbury results. Note the following discussion is for regional samples only; a discussion of metal levels found in urban residential soils, which tend to include samples closer to the smelters, is provided in Section 4.3 below.

Table 4.2 **Summary of COC Concentrations (mg/kg) in Regional Surface Soils (*n* = 385)**

Parameter	Minimum	Maximum	Mean	Standard deviation
Arsenic	ND	305	14.8	21.3
Cadmium	ND	3.2	0.36	0.54
Cobalt	2.0	78.5	12.5	10.3
Copper	6.1	3850	261	314
Nickel	14.0	2900	263	296
Lead	3.5	194	50.0	25.0
Selenium	ND	17.0	2.2	2.1

ND = below analytical detection limit.

A series of maps is provided that illustrate the concentration of each of the COC (As, Co, Cu, Ni, Pb, Se) in surface soils to a distance of approximately 20 km from the smelter centers. In general, elevated concentrations of metals were centered on the three historic smelting centers of Coniston, Copper Cliff and Falconbridge. This is clearly illustrated in Figures 4.1 to 4.6. Although the actual soil sampling extended over a vast area approximately 200 km × 200 km, the major influence of the smelters is much more localized. The actual extent of effects from smelter emissions on regional background concentrations is thought to extend out about 120 km. This is discussed in more detail in Section 4.2.3 below.

4.2.2.1 Arsenic

The maximum value for As in the 0–5 cm samples was 305 mg/kg, with minimum values below detection limits. The regional arithmetic mean value was 14.8 mg/kg, which compares with an upper crustal average of 4.8 mg/kg (Rudnick and Gao 2003). The Table F Ontario background concentration is 17 mg/kg and the MOE Table A effects-based generic guideline is 20 mg/kg. The Table A limit was exceeded in 113 samples. The elevated As concentrations are centered on the Coniston, Vale and Xstrata smelters (Figure 4.1).

It is apparent that large portions of the Sudbury area between the smelters of Copper Cliff and Falconbridge contain soils with As concentrations <20 mg/kg. This may be attributed to residents importing, vertically mixing or amending soil in their yards. This pattern also appears for the other COC. Soils with elevated As values are localized within a few kilometers of the smelters. Soils with As levels more than 200 mg/kg (10 × the Table A value) only occur in the town of Falconbridge.

During surveys from 1976 to 1997 in the Sudbury area, the MOE recorded a maximum soil As level of 510 mg/kg in 1976 in a sample approximately 2 km north of the Xstrata smelter (MOE 2001). Table 4.3 contains soil metal data for some other mining related sites in Canada and Australia. The maximum As level in soil surrounding the smelter at Trail, British Columbia was reported to be 130 mg/kg (Intrinsik 2007), while the maximum soil As level at the Deloro site in Ontario was 605 mg/kg (Cantox 1999). The MOE (1991) detected soil As levels ranging up to 234 mg/kg in residential areas of Port Hope and up to 1045 mg/kg in Wawa (MOE 1999). Residential communities in both of these Ontario towns were impacted by historic smelting emissions.

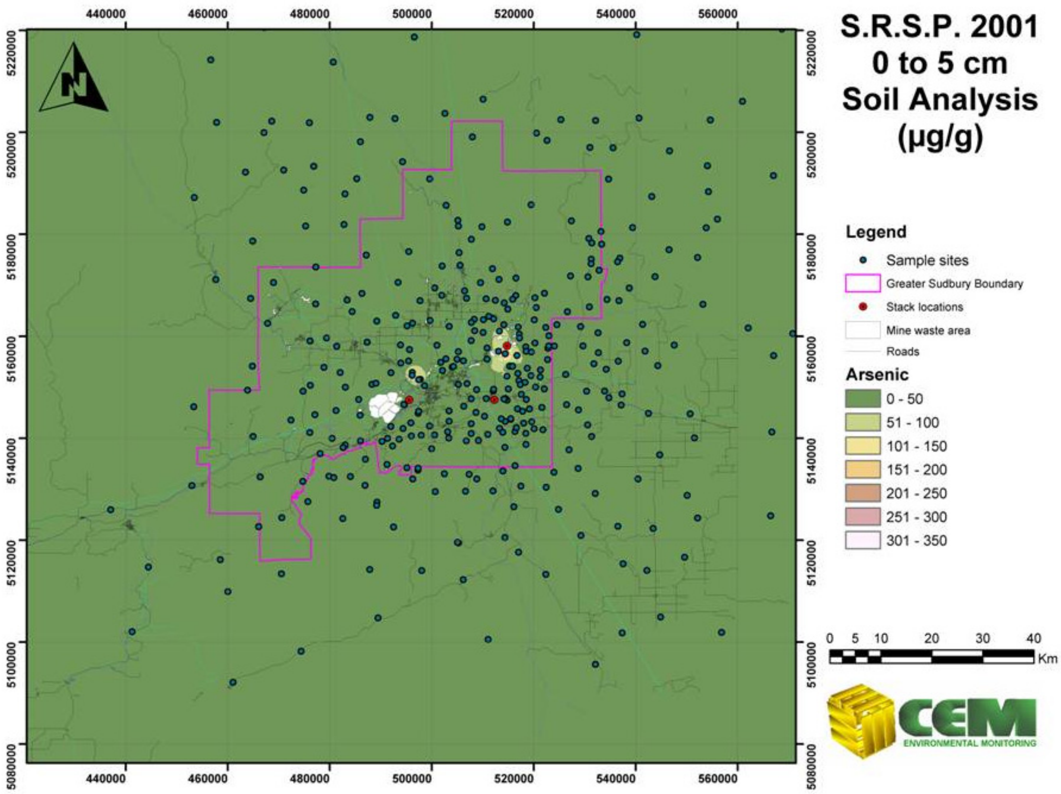

Figure 4.1 **Regional Distribution of Arsenic (mg/kg)**

Table 4.3 **Summary of Soil Metal Levels (mg/kg) Reported in Other Mining-related Risk Assessments**

Location (Reference)	Statistic	As	Co	Cd	Cu	Pb	Ni	Se
Port Colborne, Ontario (MOE 2002)	Range *n* = >100	ND–350	5–262	ND–5.1	4–2720	6–1800	19–17,000	0.1–19.4
	Mean	16	51	1.2	240	217	2508	2.4
Trail, British Columbia (Intrinsik 2007)	Range *n* = 364	1.2–130		0.1–27.6	2–326	2–3330		
	Mean	17.7		3.2	23	207		
Deloro, Ontario (Cantox 1999)	Range *n* = 147	2.4–605	5.1–340		6–115	3.5–655	8.8–195	
	Mean	111	57		29	122	44	
Mt Isa, Australia (Taylor et al. 2010)	Range n[1] = 60			0.7–12	31–12,100	8–5700		
	Mean			1.8	342	105		

n = sample size; ND = Not detected.

[1] For fine texture soils.

4.2.2.2 Cobalt

Elevated concentrations of Co in surface soils are not widely distributed throughout the study area (Figure 4.2). Soils with Co concentrations above Table A for residential land use and coarse soils are primarily confined to the immediate vicinity of the three smelting centers of Copper Cliff, Coniston and Falconbridge. Several sample sites in the Sudbury area have concentrations above the Ontario soil quality guideline of 40.0 m/kg.

With a range in concentration from 2 to 78 mg/kg, the arithmetic mean Co levels (12.5 mg/kg) in soil surface layers of the Sudbury region are slightly lower than those described by McKeague et al. (1979) for the surface mineral horizon of Shield soils. The mean Co level in this study was very similar to that (11 mg/kg) reported by Dudka et al. (1995) in a survey of 73 locations around Sudbury (maximum 113 mg/kg). The mean value was also similar to that defined for U.S. soils (10 mg/kg) by Shacklette et al. (1971) and Gough et al. (1988). Yakovlev et al. (2008) reported Co levels ranging from 384 to 1229 mg/kg in soil samples collected near the Norilsk Nickel Company smelter in Russia, which are substantially higher than those levels found in Sudbury.

The MOE collected and analyzed soil samples at 92 locations around Sudbury on a regular basis from 1971 to 1999. During those years, the maximum soil Co level recorded was 788 mg/kg in a sample collected in 1971 approximately 5 km west of the Copper Cliff smelter (MOE 2001). The maximum soil Co level detected in 1999 was much lower at 57 mg/kg (MOE 2001).

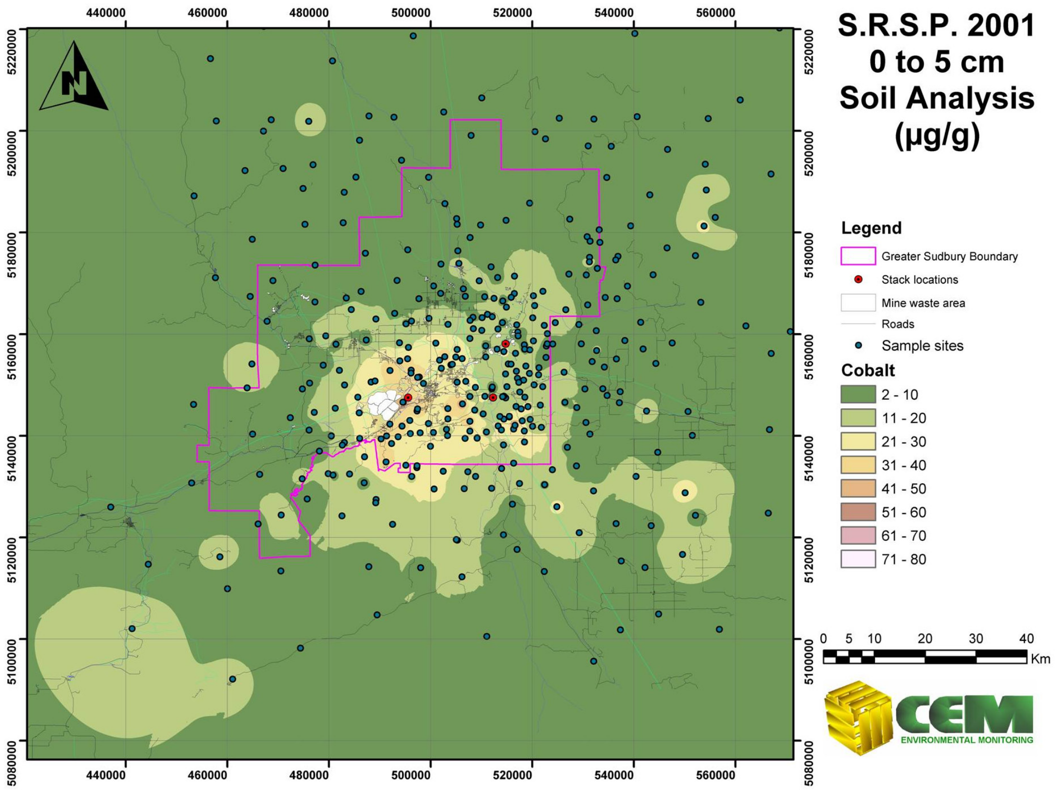

Figure 4.2 **Regional Distribution of Cobalt (mg/kg)**

4.2.2.3 Copper

The overall mean level of Cu (261.4 mg/kg) for the 0 to 5 cm layer of Sudbury regional surface soils was substantially greater than those defined for U.S. soils (25 mg/kg) by Shacklette et al. (1971) and Gough et al. (1988), and for surface layers of Canadian Shield soils (11 mg/kg) as documented by McKeague et al. (1979). With a range from 6 to 3850 mg/kg, the distribution of Cu in surface soils, as illustrated in Figure 4.3, shows a classic wind driven ellipsoidal pattern centered on the regional smelter complex. The soil concentrations of Cu are elevated above Table A for residential land use and coarse soils over a relatively wide area (Figure 4.3). Similar to As, many locations within the City Centre had Cu levels below Table A. Copper concentrations over 2000 mg/kg were confined to the immediate vicinity of the Copper Cliff and Falconbridge smelters.

During their regular surveys (1971 to 1999) around Sudbury, the maximum soil Cu level reported was 2800 mg/kg in a sample less than 1 km west of the Copper Cliff smelter (MOE 2001). Many soil samples contained Cu in excess of 1000 mg/kg. A subsequent survey in 2000 generally detected lower soil Cu levels with maximum values less than 1000 mg/kg (MOE 2001). Another survey of Sudbury soils ($n = 73$) reported a mean Cu concentration of 116 mg/kg, with a maximum value of 1891 mg/kg (Dudka et al. 1995).

Taylor et al. (2010) reported that soil Cu levels ranged from 31 to 12,100 mg/kg in soils surrounding the Xstrata Nickel smelter at Mt Isa City, Australia (Table 4.3), while Yakovlev et al. (2008) reported Cu levels up to 15,000 mg/kg in soil around the Norlisk Nickel smelter in Russia. These are considerably higher than maximum soil Cu levels found near the Trail smelter (326 mg/kg) or at the Deloro site in Ontario (115 mg/kg) shown in Table 4.3. The measured mean humus concentration of Cu in soils formed in tills within 5 km of the Flin Flon region of Manitoba was 1970 mg/kg (McMartin et al. 1999).

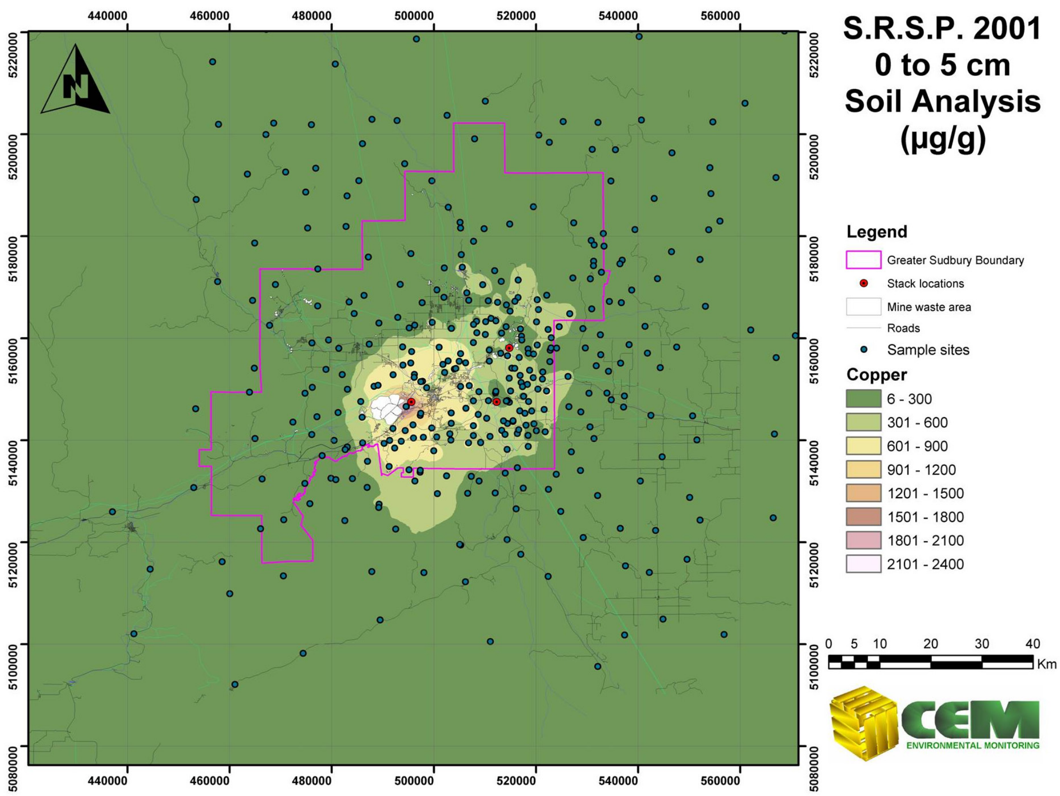

Figure 4.3 **Regional Distribution of Copper (mg/kg)**

4.2.2.4 Nickel

The distribution of Ni levels in surface soils very closely resembles the pattern of Cu (Figure 4.4). Many locations within the City Centre have Ni levels below the provincial soil quality guideline. This can likely be attributed to importing, amending or vertically mixing soils in residential or park properties.

The arithmetic mean Ni level (263 mg/kg) for the Sudbury region was much higher than those levels documented in the review by McKeague et al. (1979) for agricultural soils of the Shield (12 mg/kg) and in the USGS documented levels for the conterminous U.S. soils (20 mg/kg) (Shacklette et al. 1971; Gough et al. 1988). The range of the 0 to 5 cm soil layer Ni concentrations was from 14 to 2900 mg/kg, with the higher concentrations found near the smelter operations (Figure 4.4). The Ni concentrations for the 0 to 5 cm layers in the core of the study area were considerably above the MOE Table A (150 mg/kg) guidelines for surface materials where soil pH is 5.0 to 11.0. The maximum Ni levels measured in this survey were higher than those recorded by the MOE during their regular soil surveys of Sudbury. The previous maximum Ni value was 2300 mg/kg reported in a 1997 sample less than 1 km east of the Copper Cliff smelter (MOE 2001). The maximum value reported from the 1999 and 2000 surveys was 1000 mg/kg (MOE 2001). Another survey of Sudbury soils ($n = 73$) reported a mean Ni concentration of 105 mg/kg, with a maximum value of 2149 mg/kg (Dudka et al. 1995).

For comparison, the measured mean background concentration of Ni in the humus layers of soils formed in tills in the Flin Flon region of Manitoba was 7 mg/kg (McMartin et al. 1999). In Rouyn, on the other hand, Henderson et al. (2002) reported levels of Ni in the humus layers of 20.5 mg/kg, with a range of 7 to 82 mg/kg, levels much lower than in the soils of the Sudbury region. Yakovlev et al. (2008) reported Ni levels up to 2915 mg/kg in soils surrounding the Norilsk smelter in Russia, while Ni levels in residential soils in Port Colborne, Ontario, ranged from 19 to 17,000 mg/kg, with a mean Ni concentration of 2508 mg/kg (MOE 2002). In undisturbed soil of deciduous woodlots between 1 and 2 km east (downwind) of the Port Colborne Ni refinery, the Ni levels ranged up to 33,000 mg/kg (Jacques Whitford Limited 2004).

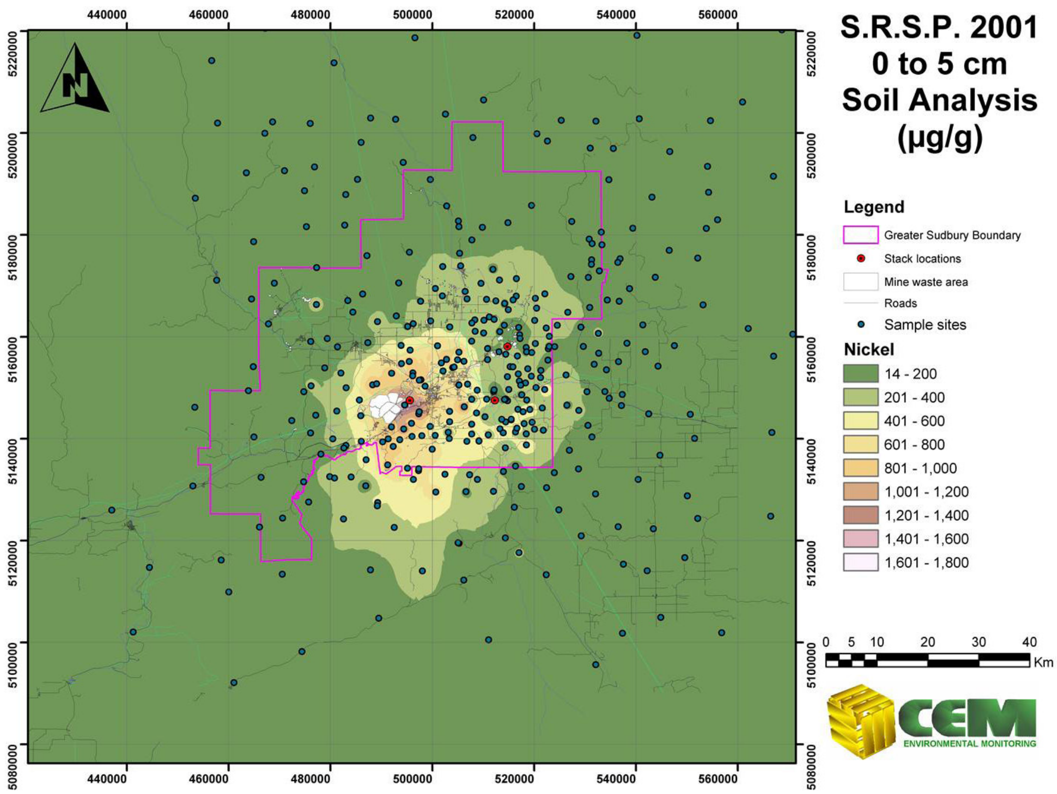

Figure 4.4 **Regional Distribution of Nickel (mg/kg)**

4.2.2.5 Lead

The distribution of Pb in surface soils was somewhat more patchy than the other elements (Figure 4.5). Soils containing Pb above the Ontario soil quality guideline (200 mg/kg) were primarily confined to the three smelting centers, with the largest density of these samples in proximity to the Copper Cliff smelter. Samples containing 100 to 200 mg/kg were primarily situated between the smelting centers, with samples containing 50 to 100 mg/kg being more widespread.

With a range in concentrations from 3.5 to 194 mg/kg, the mean regional value for Pb (50 mg/kg) in Sudbury area soil (0 to 5 cm) was higher than that documented by Dudas and Pawluk (1980) for Prairie soils, by McKeague et al. (1979) for soils of the Shield region (20 mg/kg) and by Shacklette et al. (1971) and Gough et al. (1988) for conterminous U.S. soils (20 mg/kg). Lead levels in soils surrounding the smelter at Trail, British Columbia, ranged from 6 to 3330 mg/kg (Intrinsik 2007).

In previous surveys of Sudbury, the MOE reported a maximum soil Pb level of 1000 mg/kg near the Copper Cliff smelter in 1986. A subsequent survey in 1999 did not reveal any soil samples exceeding background (120 mg/kg, MOE 1997), while the maximum soil Pb level in 2000 was only 160 mg/kg, with the Table A effects-based guideline of 200 mg/kg (MOE 1997) being exceeded at only two sites (MOE 2001).

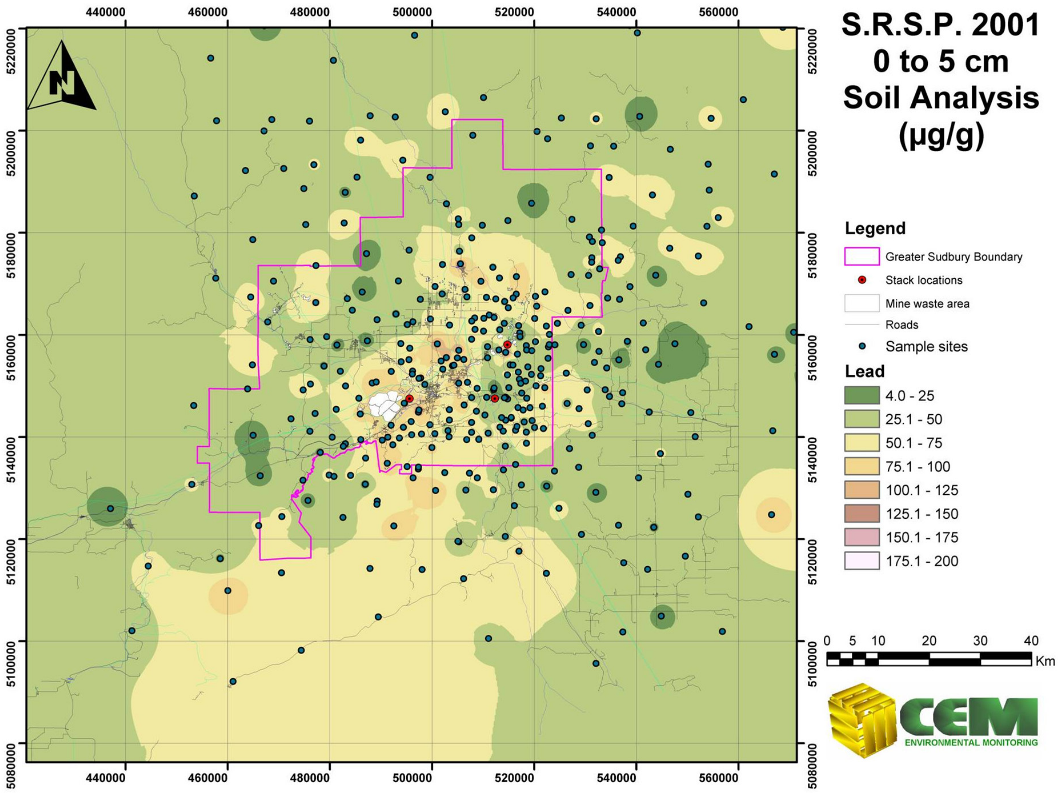

Figure 4.5 **Regional Distribution of Lead (mg/kg)**

4.2.2.6 Selenium

The soil concentrations of Se were generally low throughout the study area (Figure 4.6). The primary exception was soil samples in the immediate vicinity of Copper Cliff, which were elevated above the provincial Table A effects-based soil quality guideline (10 mg/kg). The distributional map for Se (Figure 4.6) also illustrates the classic ellipsoidal nature characteristic of aerosol deposition of a point source origin, with a locus near the Copper Cliff smelting operations. The highest concentration zone was immediately to the north-east of the Copper Cliff operations. During their 1971–1999 regular surveys, the MOE reported that Se concentrations rarely exceeded the Table A guideline, and were only elevated near the Copper Cliff smelter, with two soil samples containing Se levels of 11 and 33 mg/kg MOE (2001). During the survey in 2000 ($n = 103$ sites), the MOE reported that Se only rarely exceeded background (1.9 kg/kg) values and the maximum measured was just 3.7 mg/kg. However, it appears that Se was not measured in many of the samples from that year for some reason.

The arithmetic mean selenium level (2.2 mg/kg) for the 0 to 5 cm layer of undisturbed soils the Sudbury region was higher than documented in the review by McKeague et al. (1979) for agricultural soils of the Shield (0.18 mg/kg). The Sudbury Se levels were similar to the mean Se concentration (2.4 mg/kg) in soil reported in Port Colborne, Ontario (MOE 2002). Few of the other studies reported soil Se concentrations.

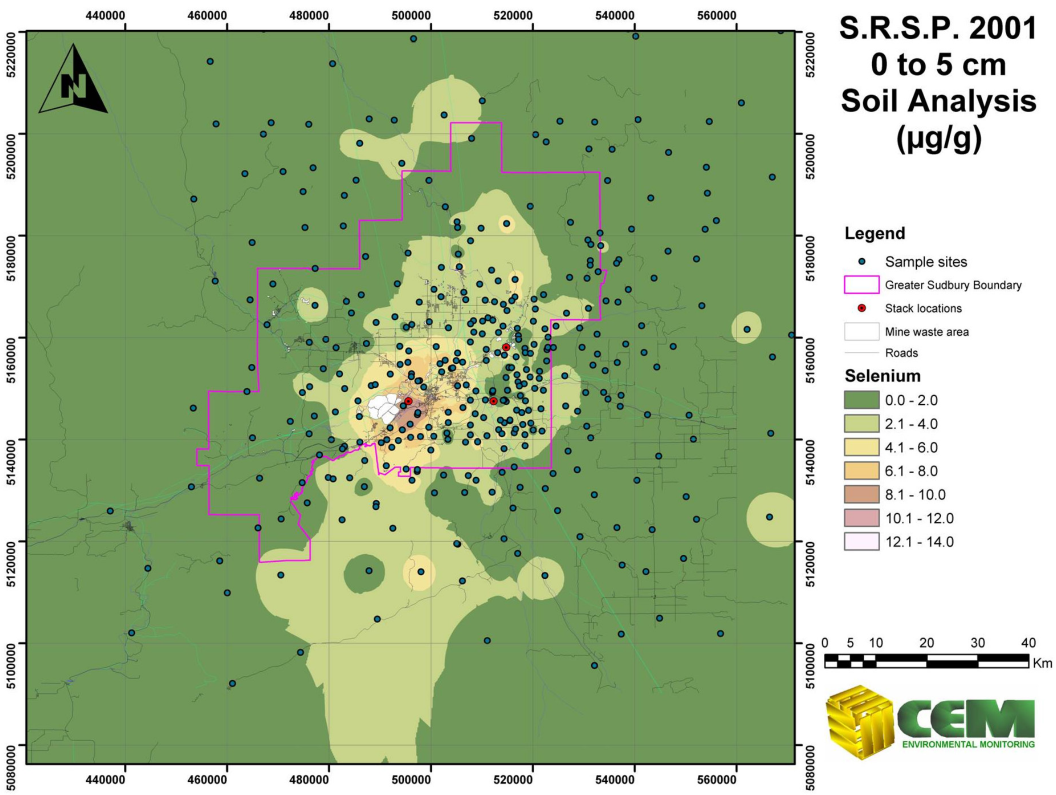

Figure 4.6 **Regional Distribution of Selenium (mg/kg)**

4.2.3 Zonation of Metal Enrichment in the Sudbury Smelter Footprint

The regional geochemical maps (Figures 4.1 to 4.6) indicate that the loading of the aerosol particular fallout from the regional smelters follows an ellipsoid, with a dominant southwest–northeast axis. The graphs in Figure 4.7 illustrate the concentrations of the individual anthropogenic metal(loid)s along a gradient from the center of the smelter zone toward regional background approximately 120 km from the heart of Sudbury. This estimate of the regional impact of smelter emissions agrees well with those estimated using metal accumulation on lichen thalli as deposition indices (Tomassini and Neiboer 1976). This estimate also compares with a calculated distance to regional background in humus of between 50 and 110 km (Zoltai 1988; McMartin et al. 1999; Henderson et al. 2002) for the smelter in the Flin Flon area of Manitoba, and a zone of 40 to 50 km for the Horne Smelter in the Rouyn-Noranda area of Quebec (Henderson et al. 2002). Goodarzi et al. (2001) documented enrichment of a series of six elements (As, Cd, Cu, Hg, Pb and Zn) in soils of the Trail, British Columbia area to a distance of 26 km from the smelter. Using associated moss bag studies, the authors concluded that the enrichment of Hg and As in the regional soils was not attributed to smelter activity. These authors emphasized the need for high quality atmospheric deposition data to supplement, and help to explain, data obtained from regional soil survey data.

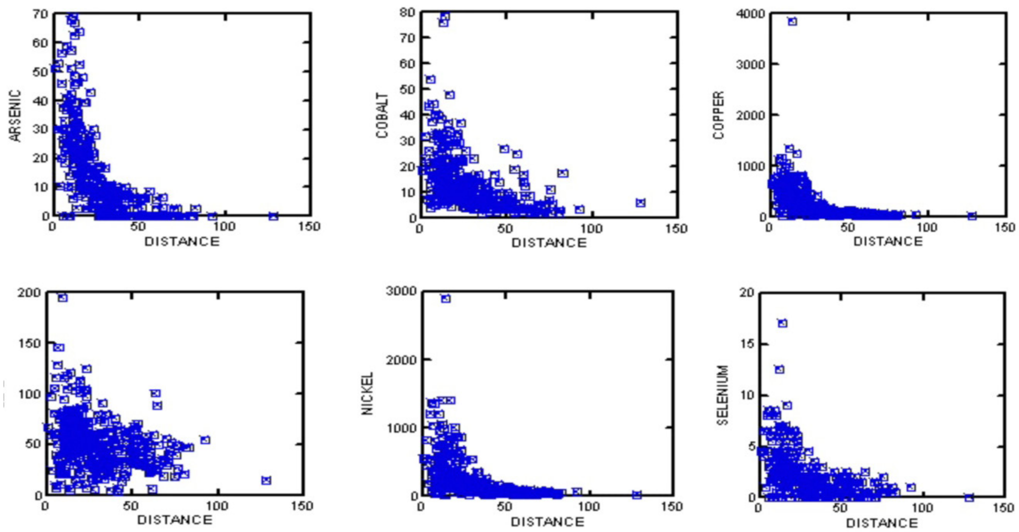

Figure 4.7 **Graphs Illustrating the Concentrations of Individual Metal(loid)s with Distance (km) from the Smelter Zone Centroid (from CEM 2004)**

The data in Table 4.4 summarize the mean concentrations of 20 elements in the 0 to 5 cm layer of the soils of this study in a series of circular zones around the center of smelter activity in the Sudbury region. The circular zonation does not exactly mimic the ellipsoidal zone suggested by wind rose and extrapolated map concentration data (Figures 4.1 to 4.6) but does provide an indication of the decrease in anthropogenic metal concentration in the surface soils with distance, to a final distance of 100 km at the borders of the current study zone.

The non-smelter emitted elements (Al, Ca, Mg, Mn, Ba, Be, Cr, Sr, V and Zn) tend to generally exhibit a similar concentration in the surface layer throughout the zones of the region, with no obvious enrichment pattern in the 0 to 5 cm layer. Some of these elements (Ca, Mn and Sr) actually are depleted in the surface layer nearer to the center of the smelter zone. This depletion perhaps reflects the effects of earlier higher levels of soil acidification from the high sulfur dioxide washout to regional soils before the implementation of the modern control systems. These control systems have resulted in the sulfur dioxide from the smelting process being converted into sulfuric acid, a valuable by-product of the mineral extraction process.

The metal(loid)s which are influenced by anthropogenic or smelter processes, on the other hand, show distinct concentration drops in the 0 to 5 cm layer with distance from the smelter zone, a characteristic response to point source emissions documented in most studies (e.g. Zoltai 1988; McMartin et al. 1999; Nikonov et al. 1999; Goodarzi et al. 2001; Henderson et al. 2002; Koptsik et al. 2003). The last zone (60 to 100 km) may exaggerate the drop in concentration with distance because the data are predominantly from the outer portion of the survey region with the 16 km cells at the extreme corners of the square.

Table 4.4 **Mean Concentration of Metal(loid)s (mg/kg) in the 0 to 5 cm Layer of Soils within Concentric Zones around the Sudbury Smelter Region.**

Parent Material Influence Metals								
	Aluminum	Calcium	Magnesium	Manganese	Chromium	Strontium	Vanadium	Zinc
0–5 km	8564	2036	1510	220	37	23	26	35
5–15 km	9980	2649	1918	265	38	28	31	39
15–30 km	10,054	3286	1853	308	40	35	31	40
30–60 km	9730	3154	1773	344	38	35	32	39
60–100 km	8720	3025	1556	343	36	33	29	41

Anthropogenic Influence Metal(loid)s								
	Arsenic	Cadmium	Cobalt	Copper	Iron	Lead	Nickel	Selenium
0–5 km	30	0.52	23	545	19,145	62	582	4.4
5–15 km	30	0.41	19	511	19,352	58	450	3.3
15–30 km	14	0.52	14	283	16,205	53	307	2.3
30–60 km	3.1	0.19	7.2	82	13,789	43	104	1.1
60–100 km	0.57	0.17	4.6	33	11,620	40	47	0.7
Parent material	1.11	NA	8.9	26	22,800	5.9	36	0.06

4.3 Distribution of COC within the Communities of Interest (COI)

The following sections summarize soil metal concentrations in the five COI (Copper Cliff, Coniston, Falconbridge, Hanmer, and Sudbury Centre) that were selected for detailed examination in the Human Health Risk Assessment (HHRA) (see Chapter 5). It was necessary to develop summary statistics for each of the COI to calculate community-specific exposure values in the HHRA. This is described in more detail in Chapter 7.

4.3.1 Copper Cliff

A review of the metal concentrations for the six COC in Copper Cliff is presented in the following text. In this community, a total of 315 soil samples were analyzed from the 0 to 5 cm soil depth, with 290 soil samples analyzed from both the 5 to 10 cm and 10 to 20 cm depths. A summary of the COC concentrations in the soils of this community is provided in Table 4.5.

4.3.1.1 Arsenic

The concentration of As reported at all three soil depths ranged from 2.5 to 101 mg/kg; note the minimum value represents one-half of the MDL for As. At the 0 to 5 cm soil depth, the mean As concentration was 17.6 mg/kg. The maximum As concentration for this depth was 72 mg/kg, and the 95th percentile concentration was 44.3 mg/kg. The deepest soil sampled (10 to 20 cm) exhibited a maximum As concentration of 99 mg/kg, with a mean concentration at this depth of 23.6 mg/kg. In a detailed HHRA in a community near a smelter operated by Vale in Port Colborne, Ontario, the maximum soil As in residential soil was reported to be 350 mg/kg (MOE 2002), while soil As levels in Deloro, Ontario, ranged from 2.4 to 605 mg/kg (Cantox 1999) and in Wawa, soil As levels ranged up to 1045 mg/kg (MOE 1999).

4.3.1.2 Cobalt

The mean Co concentration in the uppermost soil layer was 32.4 mg/kg with a range from 6 to 110 mg/kg. The 5 to 10 cm soil depth exhibited a Co range of 3 to 70 mg/kg. The mean and 95th percentile concentrations at this depth were 23.3 mg/kg and 47.1 mg/kg, respectively. The 10 to 20 cm soil depth showed Co concentrations varying from 5 to 46 mg/kg, with a mean concentration of 19.9 mg/kg. Cobalt levels in Sudbury soils are slightly lower than those reported for other Ontario locations at Port Colborne (mean 51 mg/kg) and Deloro (mean 57 mg/kg).

4.3.1.3 Copper

The Cu concentrations for the 0 to 5 cm soil depth ranged from 26 to 5600 mg/kg. The reported mean and 95th percentile concentrations were 1367 mg/kg and 3430 mg/kg, respectively. Soil from the 10 to 20 cm depth showed a range of Cu concentrations from 25 to 2000 mg/kg. The mean Cu concentration at this depth was 590.0 mg/kg, whereas the 95th percentile concentration was 1300 mg/kg. Copper concentrations in Sudbury soils tended to be higher than those reported for other Ontario locations (Port Colborne, Deloro, see Table 4.3) and in soils surrounding the smelter at Trail, British Columbia (soil Cu range 2 to 326 mg/kg). However, higher soil Cu levels were reported surrounding the Norilsk Nickel smelter in Russia (range 3300 to 15,000 mg/kg; Yakovlev et al. 2008) and the Xstrata smelter at Mt. Isa in Australia (range 31 to 12,100 mg/kg; Taylor et al. 2010).

4.3.1.4 Nickel

The range of Ni concentrations in the uppermost soil layer (0 to 5 cm) was 24 to 3700 mg/kg, with an average concentration of 978 mg/kg. In comparison, the 95th percentile concentration for this depth was 2500 mg/kg. The mean Ni concentration in the 5 to 10 cm soil depth was 720 mg/kg. The Ni concentration range at this depth was 40 to 3100 mg/kg, with a 95th percentile concentration of 1755 mg/kg. Soil Ni levels tended to be lower in the deeper soils but were still elevated relative to background concentrations. The 10 to 20 cm soil depth demonstrated Ni concentration values from 27 to 1900 mg/kg. The mean concentration in this lowermost depth was 582 mg/kg, with a 95th percentile concentration of 1200 mg/kg.

In contrast, soil Ni concentrations in residential soils from Port Colborne, Ontario, ranged from 19 to 17,000 mg/kg (MOE 2002). The distribution of soil Ni concentrations in this study was quite skewed as the mean soil Ni level was 2508 mg/kg, much lower than the maximum value but still higher compared to Sudbury soils. Yakovlev et al. (2008) reported Ni levels ranged from 870 to 2915 mg/kg in soils collected around the Norilsk smelter in Russia.

4.3.1.5 Lead

Lead concentrations in the upper soil layer ranged from 3 to 410 mg/kg. The mean Pb concentration in the upper 5 cm of soil was 83.0 mg/kg and the 95th percentile concentration was 220 mg/kg. The Pb concentrations at the 5 to 10 cm depth ranged from 7 to 330 mg/kg, with an average concentration of 71.9 mg/kg. The reported 95th percentile concentration was 190 mg/kg at this soil depth. The deepest soil sampled (10–20 cm) demonstrated an average Pb value of 85.9 mg/kg. The maximum soil Pb concentration was actually found at this depth (610 mg/kg) which might be attributed to soil mixing, or possibly a source of Pb other than the smelters.

Much higher soil Pb concentrations have been reported in other locations (Table 4.3) compared to the Sudbury values. For example, maximum soil Pb concentrations reported in Port Colborne (1800 mg/kg), Trail, B.C. (3330 mg/kg) and Mt. Isa (5700 mg/kg) are all above anything found in the Sudbury area. In a risk-based characterization of soils from an urban setting in the UK, Hooker and Nathanail (2006) reported that Pb concentrations ranged from 27 to 2853 mg/kg ($n=454$). Soil Pb levels in older residential communities in Toronto range up to 3150 mg/kg (MOE 2002).

4.3.1.6 Selenium

The minimum Se concentration for all three soil sample depths was 0.5 mg/kg; note that this value represents one-half of the MDL for Se. The mean Se value for the 0 to 5 cm soil range was 7.5 mg/kg, with a 95th percentile concentration of 19 mg/kg. The maximum Se concentration at this depth was 49 mg/kg. The mean concentration in the 5 to 10 cm soil depth was 3.9 mg/kg, with a 95th percentile concentration of 8 mg/kg. The maximum Se concentration at this depth was 14 mg/kg. The mean Se concentration in the 10 to 20 cm soil depth was 2.8 mg/kg, with a maximum concentration of 11 mg/kg. The 95th percentile concentration reported for this depth was 6 mg/kg.

Table 4.5 **Summary of Metal Concentrations (mg/kg) in Copper Cliff**

Depth (cm)	Statistic	Arsenic	Cobalt	Copper	Nickel	Lead	Selenium
0–5	Min	2.5	6	26	24	3	0.5
$n=315$	Max	72	110	5600	3700	410	49
	Mean	17.6	32.4	1367	978	83.0	7.5
	95th percentile	44.3	79.3	3430	2500	220	19
5–10	Min	2.5	3	26	40	7	0.5
$n=290$	Max	101	70	2800	3100	330	14
	Mean	22.2	23.3	779	720	71.9	3.9
	95th percentile	53.6	47.1	1655	1755	190	8
10–20	Min	2.5	5	25	27	5	0.5
$n=290$	Max	99	46	2000	1900	610	11
	Mean	23.6	19.9	590	582	85.9	2.8
	95th percentile	55.6	36.55	1300	1200	240	6

4.3.2 **Coniston**

A review of the metal concentrations for the six COC in Coniston is presented in the following text. In this COI, a total of 324 soil samples were analyzed from the 0 to 5 cm soil depth, with 304 and 288 soil samples analyzed from the 5 to 10 cm and 10 to 20 cm depths, respectively. A summary of the COC concentrations in the soils of this community is provided in Table 4.6.

4.3.2.1 **Arsenic**

The minimum As concentration reported at all three soil sampling depths was 2.5 mg/kg (one-half of the MDL for As). The mean As level in the topmost soil layer was 10.3 mg/kg, with a maximum As concentration of 66 mg/kg and a 95th percentile concentration of 33 mg/kg. The maximum As concentration in the 5 to 10 cm soil range was 53 mg/kg. The 95th percentile concentration was 28.9 mg/kg, whereas the mean concentration was 10.6 mg/kg at this depth. The 10 to 20 cm soil layer demonstrated a mean As concentration of 9.9 mg/kg (range 2.5 to 55 mg/kg) with a 95th percentile concentration of 23.7 mg/kg.

4.3.2.2 **Cobalt**

Cobalt concentrations ranged from 3 to 74 mg/kg in the 0 to 5 cm soil layer, with a mean concentration of 16.0 mg/kg. The mean Co value in the 5 to 10 cm soil layer was 13.0 mg/kg (range 3 to 46 mg/kg). At the 10 to 20 cm depth, the minimum and maximum Co concentrations were 4 and 43 mg/kg, respectively. The mean concentration in this layer was 11.9 mg/kg, with the 95th percentile concentration reported to be 22 mg/kg.

4.3.2.3 **Copper**

Concentrations of Cu in the topmost soil layer (0 to 5 cm) ranged from 8.3 to 1200 mg/kg, with a mean value of 236.2 mg/kg. The 95th percentile concentration in this soil layer was 782.5 mg/kg. The mean Cu concentration measured at the 5 to 10 cm soil depth was 213.6 mg/kg, with the concentration range encompassing 8.2 to 920 mg/kg. The Cu concentration range at the 10 to 20 cm depth was 17 to 1100 mg/kg. The mean concentration in this layer was reported to be 210.5 mg/kg, with a 95th percentile concentration of 506.5 mg/kg.

4.3.2.4 **Nickel**

The mean Ni content in the 0 to 5 cm soil layer was 320.7 mg/kg, with a 95th percentile concentration of 1100 mg/kg. The Ni concentration range in the topmost soil layer was 16 to 1900 mg/kg. The 5 to 10 cm soil depth demonstrated a mean Ni concentration of 282.4 mg/kg, with a Ni concentration range of 14 to 1200 mg/kg reported. The 10 to 20 cm soil range exhibited Ni concentrations from 22 to 1400 mg/kg with a mean concentration at this soil level of 262.4 mg/kg.

4.3.2.5 **Lead**

The minimum Pb concentration in the uppermost (0 to 5 cm) and middle (5 to 10 cm) soil layers was reported at 2 mg/kg. In the upper 5 cm of soil, the maximum Pb concentration was 400 mg/kg, and had a reported mean of 47.9 mg/kg. The 5 to 10 cm soil depth displayed a mean Pb content of 40.2 mg/kg. The maximum Pb level at this depth was 270 mg/kg, with a 95th percentile concentration of 130 mg/kg. The mean Pb concentration in the 10 to 20 cm soil depth was 43.0 mg/kg. Lead values at this soil level spanned a range of 3 to 280 mg/kg, with a 95th percentile concentration of 146.5 mg/kg.

4.3.2.6 **Selenium**

The minimum and 95th percentile Se concentrations at all three soil depths were equivalent at 0.5 mg/kg and 3 mg/kg, respectively. The minimum concentration represents one-half of the MDL for Se. The mean Se content of the 0 to 5 cm soil depth was 1.1 mg/kg, with a maximum Se concentration of 5 mg/kg. The maximum Se level in the middle soil depth (5 to 10 cm) was 4 mg/kg, and the mean concentration at this level was reported to be 1.0 mg/kg. The deepest soil layer (10 to 20 cm) exhibited a maximum Se level of 9 mg/kg, with a mean Se concentration equal to that of the middle soil layer at 1.0 mg/kg.

Table 4.6 **Summary of Metal Concentrations (mg/kg) in Coniston**

Depth (cm)	Statistic	Arsenic	Cobalt	Copper	Nickel	Lead	Selenium
0–5	Min	2.5	3	8.3	16	2	0.5
n = 324	Max	66	74	1200	1900	400	5
	Mean	10.3	16.0	236.2	320.7	47.9	1.1
	95th percentile	33	44.85	782.5	1100	140	3
5–10	Min	2.5	3	8.2	14	2	0.5
n = 304	Max	53	46	920	1200	270	4
	Mean	10.6	13.0	213.6	282.4	40.2	1.0
	95th percentile	28.85	30.85	637	895.5	130	3
10–20	Min	2.5	4	17	22	3	0.5
n = 288	Max	55	43	1100	1400	280	9
	Mean	9.9	11.9	210.5	262.4	43.0	1.0
	95th percentile	23.65	22	506.5	653	146.5	3

4.3.3 Falconbridge

A review of the metal concentrations for the six COC in Falconbridge is presented in the following text. In this COI, a total of 311 soil samples were analyzed from the 0 to 5 cm soil depth, with the exception of Pb for which 310 samples were analyzed. In the 5 to 10 cm and 10 to 20 cm depths, 286 and 282 samples were analyzed, respectively (Table 4.7).

4.3.3.1 Arsenic

The minimum As level across all three soil depths was 2.5 mg/kg, which represents one-half of the MDL for As. The maximum As concentration in the 0 to 5 cm soil range was 400 mg/kg, with a mean concentration of 65.6 mg/kg. The mean As concentration in the middle (5 to 10 cm) soil layer was 95.0 mg/kg, and the 95th percentile concentration was 307.5 mg/kg. The maximum As value at this soil depth was 570 mg/kg. The 10 to 20 cm soil depth demonstrated a mean As concentration of 76.1 mg/kg, with a maximum As concentration of 620 mg/kg. This was the highest As value recorded in the study.

4.3.3.2 Cobalt

The range of Co concentrations at the shallowest soil depth (0 to 5 cm) was 4 to 190 mg/kg, with an average Co level of 45.0 mg/kg. The mean Co concentration in the 5 to 10 cm depth was 36.3 mg/kg, with a range of 1.9 to 150 mg/kg. The 10 to 20 cm soil layer exhibited a mean Co concentration of 21.6 mg/kg, and a 95th percentile of 49 mg/kg. The Co concentration range at the lowest soil depth was 2.2 to 110 mg/kg.

4.3.3.3 Copper

The maximum Cu concentration was 3000 mg/kg at both the 0 to 5 cm and 5 to 10 cm soil depths; these depths also had identical 95th percentile concentrations of 1800 mg/kg. The minimum Cu concentration in the topmost soil level (0 to 5 cm) was 10 mg/kg, with the mean concentration at this level reported to be 706.9 mg/kg. The mean concentration in the 5 to 10 cm depth was 639.4 mg/kg, with a range of 9.5 to 3000 mg/kg. The mean soil Cu level in the 10 to 20 cm soil depth was 340.9 mg/kg, and the maximum Cu level at this soil depth was 2000 mg/kg.

4.3.3.4 Nickel

The minimum Ni concentrations in the shallowest and deepest soil depths were equivalent at 17 mg/kg; the maximum soil concentrations at both of these depths were 3700 and 2500 mg/kg, respectively. The mean soil Ni concentration in the 0 to 5 cm depth was 751.0 mg/kg. The 5 to 10 cm soil depth exhibited a concentration range of 22 to 3100 mg/kg. The average concentration at this level was 700.0 mg/kg. The deepest soil layer (10 to 20 cm) was reported to have a mean concentration of 401.7 mg/kg.

4.3.3.5 Lead

The mean Pb concentration in the 0 to 5 cm soil layer was 72.1 mg/kg, with a range of 2 to 370 mg/kg. The 95th percentile concentration in this uppermost soil layer was 190 mg/kg. The Pb range in the 5 to 10 cm layer of soil was 3.6 to 340 mg/kg. At this depth, the mean and 95th percentile Pb concentrations were 67.2 and 197.5 mg/kg, respectively. The 10 to 20 cm soil layer demonstrated a mean Pb concentration of 44.3 mg/kg with a range from 3.1 to 790 mg/kg.

4.3.3.6 Selenium

The minimum Se concentration reported for all three soil layers was 0.5 mg/kg which represents one-half of the MDL for Se. The average Se level in the upper soil layer (0 to 5 cm) was 2.5 mg/kg, with a maximum of 12 mg/kg. The maximum Se concentration exhibited by soil in the 5 to 10 cm depth was 11 mg/kg, while the mean and 95th percentile concentrations were 2.6 and 6.75 mg/kg, respectively. The average Se level in the 10 to 20 cm soil depth was 1.9 mg/kg.

Table 4.7 **Summary of Metal Concentrations in Falconbridge (mg/kg)**

Depth (cm) and number of samples (*n*)	Statistic	Arsenic	Cobalt	Copper	Nickel	Lead	Selenium
0–5	Min	2.5	4	10	17	2	0.5
n = 311	Max	400	190	3000	3700	370	12
	Mean	65.6	45.0	707	751	72.1	2.5
	95th percentile	190	110	1800	1950	190	6
5–10	Min	2.5	1.9	9.5	22	3.6	0.5
n = 286	Max	570	150	3000	3100	340	11
	Mean	95.0	36.3	639	700	67.2	2.6
	95th percentile	308	96	1800	1975	198	6.7
10–20	Min	2.5	2.2	9.5	17	3.1	0.5
n = 282	Max	620	110	2000	2500	790	8
	Mean	76.1	21.6	341	402	44.3	1.9
	95th percentile	230	49	900	1095	140	5

4.3.4 Hanmer

A review of the metal concentrations for the six COC in Hanmer is presented in the following text. Hanmer was chosen to represent a reference community, as it has similar demographics and is geologically similar to the smelter communities but the residential soils do not appear to be influenced by smelter emissions. In this COI, a total of 85 soil samples were analyzed from the 0 to 5 cm soil depth, while 30 and 28 samples were analyzed from the 5 to 10 cm and 10 to 20 cm depths, respectively. A summary of the COC concentrations in the soils of this community is provided in Table 4.8.

4.3.4.1 Arsenic

The minimum As level reported at all three soil depths was 2.5 mg/kg, representing one-half of the MDL. The maximum As value was 25 mg/kg at the 0 to 5 cm soil depth and 8 mg/kg at both of the deeper soil depths. The mean As concentrations in the three soil depths were: 4.2, 3.2, and 2.8 mg/kg, decreasing correspondingly with soil depth. Similarly, the 95th percentile values decreased with soil depth and were reported to be concentrations of 15, 7, and 4 mg/kg. The mean soil As concentrations from all three sample depths were substantially below the MOE background guideline of 17 mg/kg, so the influence of historic smelter emissions on As soil quality in Hanmer has been negligible.

4.3.4.2 Cobalt

The Co concentration range in the 0 to 5 cm soil layer ranged from 4 to 33 mg/kg. The mean Co value at this depth was 7.6 mg/kg, while the 95th percentile concentration was 17.8 mg/kg. The Co range in the middle soil layer (5 to 10 cm) was 2 to 6 mg/kg, with a mean value of 4.1 mg/kg. The 10 to 20 cm soil depth demonstrated a mean Co concentration of 4.3 mg/kg, with a range of only 3 to 5 mg/kg. The mean soil Co concentrations from all three sample depths were substantially below the MOE background guideline of 21 mg/kg, so the influence of historic smelter emissions on Co soil quality in Hanmer has been negligible.

4.3.4.3 Copper

The mean Cu concentration in the uppermost 5 cm of soil was 54.0 mg/kg with a range of 13 to 330 mg/kg. The mean concentration in the 5 to 10 cm soil layer was 25.0 mg/kg with a Cu range of 11 to 54 mg/kg. The 10 to 20 cm soil depth range showed Cu concentrations varying from 3.8 to 34 mg/kg, with a mean concentration of 17.4 mg/kg. The mean soil Cu concentrations from all three sample depths were less than the MOE background guideline of 85 mg/kg. However, some samples of surface soil did exceed normal background levels and there was a distinct vertical concentration gradient with Cu levels decreasing rapidly with depth. Therefore, the Cu soil quality in Hanmer has been influenced by historic smelter emissions, but the impact has been relatively insignificant.

4.3.4.4 Nickel

The Ni concentration in the uppermost soil segment (0 to 5 cm) varied from 16 to 297 mg/kg, and had a reported mean of 55.8 mg/kg. The 95th percentile concentration exhibited at this soil level was 217 mg/kg. The 5 to 10 cm soil depth displayed a Ni concentration range from 17 to 50 mg/kg with a mean Ni level of 34.4 mg/kg. The average Ni concentration in the 10 to 20 cm soil depth was 29.4 mg/kg with a range from 14 to 56 mg/kg. Some soil samples from all three depths exceeded the MOE background standard of 43 mg/kg and the mean Ni concentration in surface soil exceeded the guideline. When considered in combination with a decreasing vertical concentration gradient, it is apparent that the soil Ni quality in Hanmer has been noticeably influenced by historic smelter emissions.

4.3.4.5 Lead

In the top 5 cm of soil, a mean Pb level of 14.6 mg/kg was reported, with a 95th percentile concentration of 54.4 mg/kg. The Pb range in this upper soil layer was 2 to 79 mg/kg. The 5 to 10 cm soil layer, with a total Pb range of 5 to 44 mg/kg, exhibited a mean of 10.5 mg/kg. The 95th percentile value for this depth was 29.6 mg/kg. The deepest soil (10 to 20 cm) was observed to have a Pb range of 4 to 19 mg/kg, with an average Pb level of 6.9 mg/kg. The mean soil Pb concentrations from all three sample depths were substantially below the MOE background guideline of 120 mg/kg and well within levels normally found in urban communities in Ontario. Also, because of the historic use of leaded gasoline, it is common to find higher Pb levels in surface soil, and so a vertical concentration gradient is not uncommon in urban areas in the province. Therefore, it is difficult to conclude if historic smelter emissions have had any measurable impact on soil Pb quality in Hanmer.

4.3.4.6 Selenium

All three soil levels demonstrated minimum Se values of 0.5 mg/kg, which represents one-half of the MDL for Se. The 5 to 10 cm and 10 to 20 cm soil depths also exhibited a value of 0.5 mg/kg for mean, maximum, and 95th percentile values. The top soil layer was reported to have a maximum Se concentration of 3 mg/kg, with average and 95th percentile concentrations of 0.7 and 2 mg/kg, respectively. The mean soil Se concentration from all three sample depths was substantially below the MOE background guideline of 1.9 mg/kg and the vertical concentration gradient was weak and inconsistent. Therefore, it is difficult to conclude if historic smelter emissions have had any measurable impact on Se soil quality in Hanmer.

Table 4.8 **Summary of Metal Concentrations in Hanmer (mg/kg)**

Depth (cm)	Statistic	Arsenic	Cobalt	Copper	Nickel	Lead	Selenium
0–5	Min	2.5	4	13	16	2	0.5
n = 85	Max	25	33	330	297	79	3
	Mean	4.2	7.6	54.0	55.8	14.6	0.7
	95th percentile	15	17.8	198	217	54.4	2
5–10	Min	2.5	2	11	17	5	0.5
n = 30	Max	8	6	54	50	44	0.5
	Mean	3.2	4.1	25.0	34.4	10.5	0.5
	95th percentile	7	5	36.1	44.6	29.6	0.5
10–20	Min	2.5	3	3.8	14	4	0.5
n = 28	Max	8	5	34	56	19	0.5
	Mean	2.8	4.3	17.4	29.4	6.9	0.5
	95th percentile	4.1	5	30	40.9	10.6	0.5

4.3.5 Sudbury Center

A review of the metal concentrations for the six COC in the Sudbury Center is presented in the following text. In this COI, a total of 1129 soil samples were analyzed from the 0 to 5 cm soil depth, while 643 and 607 samples were analyzed from the 5 to 10 cm and 10 to 20 cm depths, respectively. The COC concentrations in the soils for this community are summarized in Table 4.9.

4.3.5.1 Arsenic

Minimum As concentrations in the three soil layers were 2.5 mg/kg which represents half of the MDL for As. The mean As concentration in the upper 5 cm of soil sampled was 6.0 mg/kg, with a 95th percentile concentration of 18 mg/kg. The maximum As concentration in this upper soil level was 65 mg/kg. In the middle (5 to 10 cm) soil range, the maximum detected As level was 39 mg/kg. The mean and 95th percentile concentrations at this depth were 6.5 and 17 mg/kg, respectively. The deepest soil layer (10 to 20 cm) contained an average of 5.8 mg/kg As, with a maximum and 95th percentile concentration of 67 and 14.7 mg/kg, respectively.

4.3.5.2 Cobalt

The minimum Co content of all three soil depths was equivalent at 3 mg/kg. The upper soil layer (0 to 5 cm) had a reported mean Co value of 11.2 mg/kg and a maximum concentration of 100 mg/kg. A mean concentration of 9.0 mg/kg Co was reported in the 5 to 10 cm soil depth, with a maximum value of 36 mg/kg. The 95th percentile concentration in this soil layer was 17 mg/kg. The 10 to 20 cm soil range contained a maximum Co level of 28 mg/kg, with a mean concentration of 8.5 mg/kg.

4.3.5.3 Copper

The 0 to 5 cm soil depth demonstrated a Cu range of 6.2 to 1800 mg/kg. The average and 95th percentile Cu concentrations were 155 and 590 mg/kg, respectively. The middle soil layer (5 to 10 cm) contained a mean Cu value of 122 mg/kg, with a range from 12 to 1100 mg/kg. The deepest soil layer (10 to 20 cm) had a reported Cu mean concentration of 94.4 mg/kg, while its 95th percentile concentration was 270 mg/kg. Concentrations of Cu in the 10 to 20 cm layer ranged from 11 to 530 mg/kg.

4.3.5.4 Nickel

Nickel concentrations in the topmost soil layer (0 to 5 cm) varied from 11 to 3284 mg/kg, with a mean value of 172 mg/kg. The 95th percentile concentration at this depth was 596 mg/kg. The mean Ni concentration in the 5 to 10 cm layer was 140 mg/kg with a range from 18 to 970 mg/kg. The deepest soil layer sampled (10 to 20 cm) contained a mean Ni level of 115 mg/kg, with a range of 15 to 820 mg/kg. The 95th percentile concentration for this soil depth was 300 mg/kg.

4.3.5.5 Lead

The reported mean Pb level in the 0 to 5 cm layer was 26.4 mg/kg, with a 95th percentile value of 101 mg/kg and a range from 1 to 320 mg/kg. The minimum Pb value reported at both of the lower soil depths (5 to 10 cm and 10 to 20 cm) was 2 mg/kg. The mean Pb level in the middle (5 to 10 cm) soil range was 24.8 mg/kg and was 21.9 mg/kg in the 10 to 20 cm depth layer. The maximum Pb concentration reported at the lowest soil depth (10 to 20 cm) was 470 mg/kg.

4.3.5.6 Selenium

Minimum Se levels reported at all three soil depths were 0.5 mg/kg which represents half of the MDL for Se. Maximum, mean, and 95th percentile Se concentrations in the 0 to 5 cm soil range were 13, 1.1, and 3.6 mg/kg, respectively. The mean Se concentration observed in the middle soil layer (5 to 10 cm) was 0.9 m/kg. The maximum and 95th percentile Se concentrations at this depth were 5 and 2 mg/kg, respectively. Mean and 95th percentile values in the 10 to 20 cm soil layer were 0.8 and 2 mg/kg, respectively, with Se concentrations peaking at 4 mg/kg.

Table 4.9 **Summary of Metal Concentrations (mg/kg) in Sudbury Center**

Depth (cm)	Statistic	Arsenic	Cobalt	Copper	Nickel	Lead	Selenium
0–5	Min	2.5	3	6.2	11	1	0.5
n = 1129	Max	65	100	1800	3284	320	13
	Mean	6.0	11.2	155	172	26	1.1
	95th percentile	18	28	590	596	101	3.6
5–10	Min	2.5	3	12	18	2	0.5
n = 643	Max	39	36	1100	970	310	5
	Mean	6.5	9.0	122	140	25	0.9
	95th percentile	17	17	379	429	84	2
10–20	Min	2.5	3	11	15	2	0.5
n = 607	Max	67	28	530	820	470	4
	Mean	5.8	8.5	94.4	115	21.9	0.8
	95th percentile	14.7	15	270	300	76	2

4.3.6 Spatial Distribution of COC within a Community

The distribution of each COC was mapped within each of the COI. Figures 4.8 and 4.9 illustrate the spatial distribution of Ni and Pb, respectively, as examples within the community of Copper Cliff. Each soil sample location is color coded to indicate a different concentration range. Visual examination of the COC distribution at this scale revealed no obvious trends along streets, or in relation to the smelter source. Several geostatistical approaches were also used to examine the spatial distribution of each metal within each of the COI to determine whether there were any apparent trends or patterns. The lack of a pattern at this localized scale was verified by the geostatistical analysis. This indicates that the distribution of metals within a community was essentially random. This was not unexpected since topsoil for residential properties has been extensively moved about and imported from different locations for landscaping. Therefore, metal levels at a particular property cannot be used to predict with confidence metal concentrations in soil on neighboring properties. This determination was important for the HHRA where it was necessary to select soil exposure point concentrations for the human exposure model (see Chapter 7). The lack of a predictable pattern also has implications if further soil sampling is required for risk management.

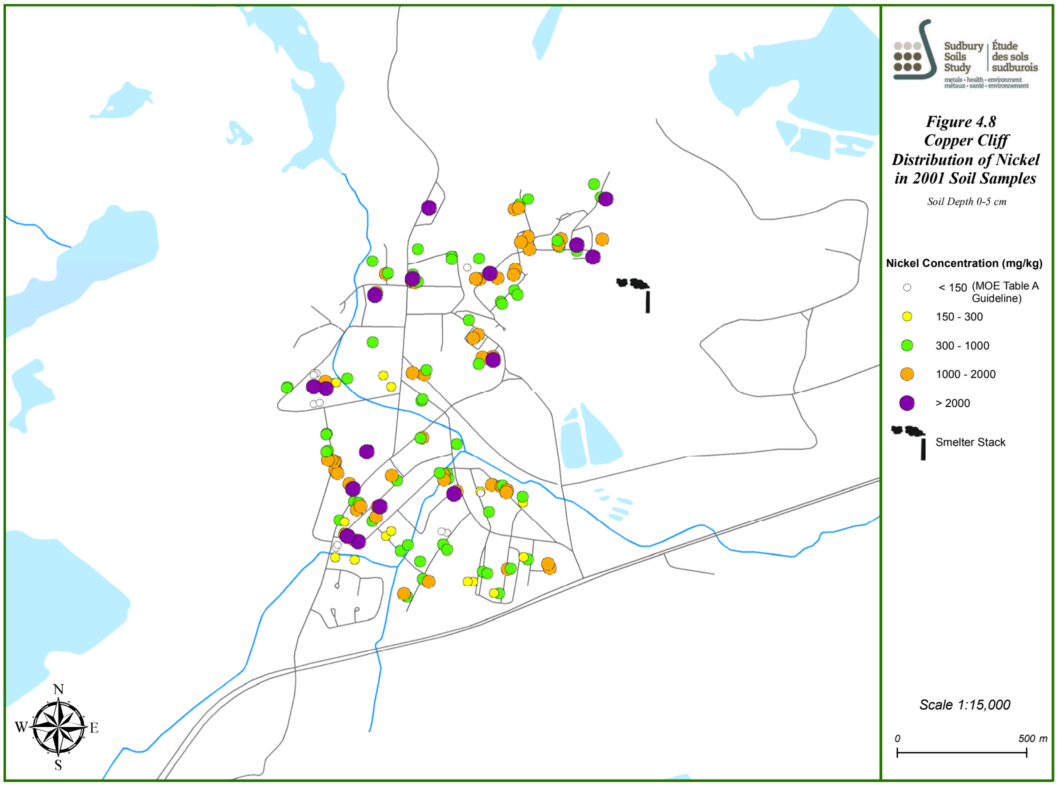

Figure 4.8 **Distribution of Ni within Town of Copper Cliff**

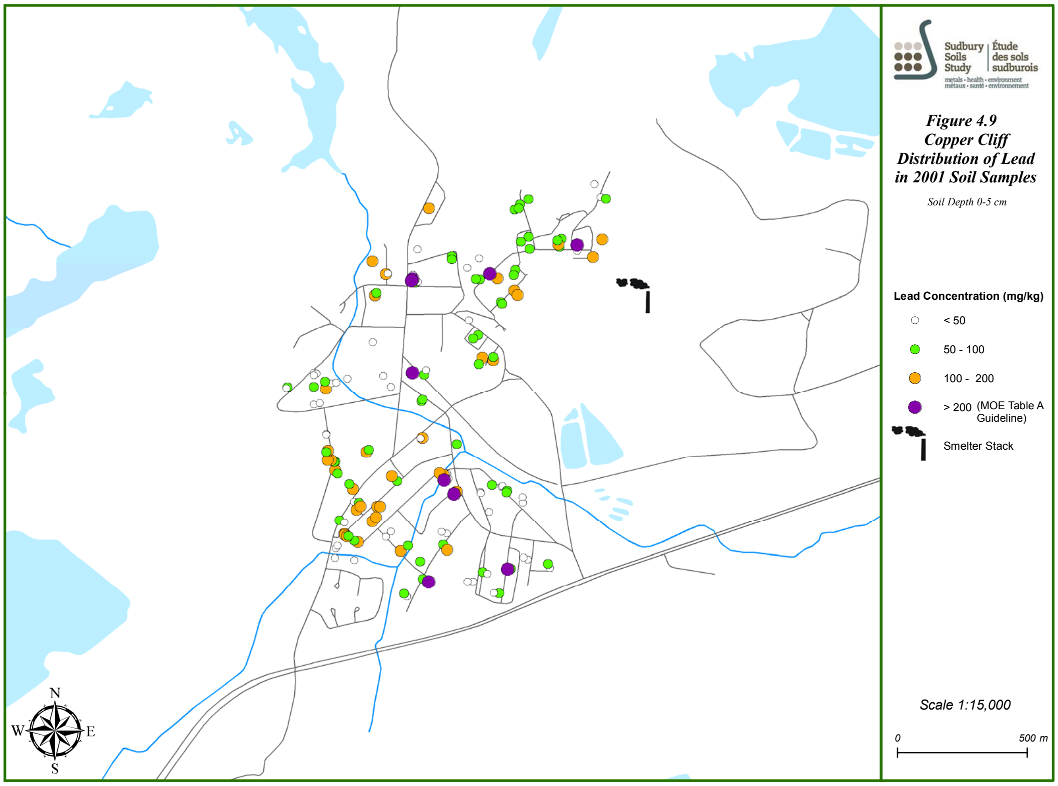

Figure 4.9 **Distribution of Pb within Town of Copper Cliff**

4.4 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

Agriculture Canada Expert Committee on Soi1 Survey (1987) The Canadian system of soil classification, 2nd edn. Agriculture Canada Publication 1646. Agriculture Canada, Ottawa, Ontario, 164 pp

Barnett PJ, Bajc AF (2002) Quaternary geology. In: Physical environment of the City of Greater Sudbury. Special Volume 6, pp. 57–86. Ontario Geological Survey, Ontario

Bohn HL, McNeal BL, O'Connor GA (2001) Soil chemistry. John Wiley & Sons, Inc., New York, 307 pp

CANTOX (1999) Deloro Village exposure assessment and health risk characterization for arsenic and other metals. Final Report to Ontario Ministry of the Environment. Cantox Environmental, Toronto

CEM (2004) Metal levels in the soils of the Sudbury Smelter footprint. Report prepared by Centre for Environmental Monitoring (CEM), Laurentian University, Sudbury

Dredge LA, Cowan WR (1989) Quaternary geology of the southwestern Canadian Shield. Volume v.K–1 (no. 1), pp. 214–249. Geological Society of America (Geological Survey of Canada), Ottawa

Dressler BO, Gupta VK, Muir TL (1991) The Sudbury structure. In: The geology of Ontario. Special Volume 4, Part 1, pp. 593–625. Ontario Geological Survey, Ontario

Dudas MT, Pawluk S (1980) Natural abundance and mineralogical partitioning of trace elements in selected Alberta soils. Can J Soil Sci 62:763–771

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

Gillespie JE, Acton CJ, Hoffman DW (1983) Soils of Sudbury area. Soil Survey Report. Ontario Institute of Pedology, Ontario

Goodarzi F, Sanei H, Duncan WF (2001) Monitoring the distribution and deposition of trace elements associated with the zinc-lead smelter in the Trail area, British Columbia, Canada. J Environ Monit 3:515–525

Golder Associates Ltd. (2001) Town of Falconbridge soil sampling program comprehensive Falconbridge Survey. Unpublished report prepared for Falconbridge Ltd. Golder Associates Ltd, 14 pp

Gough LP, Severson RC, Shacklette HJ (1988) Element concentrations is soils and other surficial materials of Alaska. Professional Paper 1458. United States Geological Survey

Gundermann DG, Hutchinson TC (1995) Changes in soil chemistry 20 years after the closure of a nickel-copper smelter near Sudbury, Ontario, Canada, pp. 559–562. Elsevier, Amsterdam, New York

Hazlett PW, Rutherford GK, van Loon GW (1983) Metal contaminants in surface soils and vegetation as a result of nickel/copper smelting at Coniston, Ontario, Canada. Reclam Reveg Res 2:123–127

Henderson PJ, Knight RD, McMartin I (2002) Geochemistry of soils within a 100 km radius of the Horne Cu smelter, Rouyn-Noranda, Québec. Geological Survey of Canada Open File Report 4169. Geological Survey of Canada

Hooker PJ, Nathanail CP (2006) Risk-based characterization of lead in urban soils. Chem Geol 226:340–351

Intrinsik (2007) Ecological risk assessment for Teck Cominco Operations at Trail, British Columbia. Final report. Terrestrial Risk Modeling Level of Refinement #3. Intrinsik Environmental Sciences, Calgary, Alberta, 143 pp

Jacques Whitford Limited (2004) Community based risk assessment, Port Colborne, Ontario. Ecological Risk Assessment – Natural Environment. Jacques Whitford Limited

Koptsik S, Koptsik G, Livantisova S, Eruslankina L, Zhmelkova T, Vologdina Zh (2003) Heavy metals in soils near the nickel smelter: chemistry, spatial variation, and impacts on plant diversity. J Environ Monit 5:441–450

McKeague JA, Desjardins JG, Wolynetz MS (1979) Minor elements in Canadian soils. Agriculture Canada, Research Branch, 75 pp

McMartin I, Henderson PJ, Nielsen E (1999) Impact of a base metal smelter on the geochemistry of soils of the Flin Flon region, Manitoba and Saskatchewan. Can J Earth Sci 36:141–160

MOE (1991) Assessment of human health risk of reported soil levels of metals and radionuclides in Port Hope. Hazardous Contaminants Branch, November 1991, ISBN 0-7729-9065-4, Ontario Ministry of the Environment, Toronto

MOE (1997) Guidelines for use at contaminated sites in Ontario. Ontario Ministry of the Environment, Toronto

MOE (1999) Studies of the terrestrial environment in the Wawa Area, 1998–1999. Phytotoxicology and Soil Standards Section, Standards Development Branch. Report No. SDB-047-3511-1999. Ontario Ministry of the Environment, Toronto

MOE (2001) Metal levels in soil and vegetation in the Sudbury area (Survey 2000 and additional historic data). Report SDB-045-3511-2001. Ontario Ministry of the Environment, Toronto

MOE (2002) Soil investigation and human health risk assessment for the Rodney Street community, Port Colborne. www.ene.gov.ca/envision/techdocs/4255e. Ontario Ministry of the Environment, Toronto

Nikonov VV, Lukina NV, Frontas'eva MV (1999) Trace elements in Al-Fe-Humus podzolic soils subjected to aerial pollution from the apatite-nepheline production industry. Eurasian Soil Sci 32(12):1331–1339

Rudnick RL, Gao S (2003) Composition of the continental crust. In: Rudnick RL (ed) The Crust, Vol. 3 Treatise on Geochemistry (eds. Holland HD and Turekian KK). Elsevier-Pergamon, Oxford, pp. 1–64

Shacklette HJ, Hamilton JC, Boerngen JG, Bowles JGM (1971) Elemental composition of surficial materials in the conterminous United States. Professional Paper 574-D. United States Geological Survey

Shotyk W, Blaser P, Grunig A, Cheburkin A (2000) A new approach for quantifying cumulative anthropogenic, atmospheric lead deposition using peat cores from bogs: Pb in eight Swiss peat bog profiles. Sci Total Environ 249:281–295

Shotyk W, Weiss D, Kramers JD, et al. (2001) Geochemistry of the peat bog at Etang de la Gruère, Jura Mountains, Switzerland, and its record of atmospheric Pb and lithogenic trace elements (Sc, Ti, Y, Zr, Hf and REE) since 12,370 14C yr BP. Geochim Cosmochim Acta 65(14):2337–2360

Shotyk W, Weiss D, Heisterkamp M, Cheburkin AK, Adams FC (2002) A new peat bog record of atmospheric lead pollution in Switzerland: Pb concentrations, enrichment factors, isotopic composition, and organolead species. Environ Sci Technol 36(18):3893–3900

Spiers GA, Pawluk S, Dudas MJ (1984) Authigenic mineral formation by solodization. Can J Soil Sci 64:515–532

Spiers, GA, Pearson DAB, Prevost F (2002) Distribution of Anthropogenic Metals in Soils of the Sudbury Smelter Footprint: Presented at the 5th International Nickel Conference, Murmansk, Russia

Taylor MP, Mackay AK, Hudson-Edwards KA, Holz E (2010) Soil Cd, Cu, Pb and Zn contaminants around Mount Isa city, Queensland, Australia, Potential sources and risks to human health. Appl Geochem 25:841–855

Yakovlev AS, Plekhanova IO, Kudryashov SV, Aimaletdinov RA (2008) Assessment and regulation of the ecological state of soils in the impact zone of mining and metallurgical enterprises of Norilsk Nickel Company. Environ Soil Sci 41(6):648–659

Zoltai S (1988) Distribution of base metals in peat near a smelter at Flin Flon, Manitoba. Water Air Soil Pollut 37:217–228

Appendix Chapter 4: Abbreviations

COC, chemicals of concern

COI, community(ies) of interest

HHRA, human health risk assessment

LFH horizons, refers to surface organic soil layers ranging in thickness from 2 to 15 centimeters. The designation LFH refers to the fresh plant detritus (L = litter) on the soil surface, the partially decomposed organic layer (F = fermentation) and the well-decomposed organic layer (H = humus)

MDL, method detection limit

MOE, Ontario Ministry of the Environment

***n*,** sample size

ND, not detected; below analytical detection limit

S.R.S.P., Sudbury regional soils project

UCL, upper confidence level