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Natural and anthropogenic metal inputs to soils in urban Uppsala, Sweden

K. Ljung[1,3], E. Otabbong[1] & O. Selinus[2]
[1]*Department of Soil Science, Swedish University of Agricultural Sciences,*
P.O. Box 7014, SE-750 07 Uppsala, Sweden
[2]*Geological Survey of Sweden, BOX 670, SE-751 28 Uppsala, Sweden*
[3]*Author for correspondence (tel.: +46-18-67-1245, +46-18-67-1248; fax: +46-18-67-2795;*
e-mail: Karin.Ljung@mv.slu.se)

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Abstract

Urban soils are complex systems due to human activities that disturb the natural development of the soil horizons and add hazardous elements. Remediation projects are common in urban areas and guideline values are set to represent a desired level of elements. However, the natural content of trace elements may not always equal the desired levels. In this study, an attempt is made to distinguish between metals that are present in the soil due to natural origins and to anthropogenic origins. Seventy-five soil samples of the 0–5, 5–10 and 10–20 cm layers were collected from 25 sites in urban areas of Uppsala City and analysed for aluminium (Al), arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), mercury (Hg), manganese (Mn), nickel (Ni), lead (Pb), tungsten (W) and zinc (Zn) using aqua regia for digestion. In order to highlight elements of geological origin, the results were compared to a similar study carried out in Gothenburg City, which has about three times as many inhabitants as Uppsala and has a more industrial history. A cluster analysis was also performed to distinguish between elements of natural and anthropogenic origin. Contents of As, Al, Fe, Cr, Ni, Mn and W in Uppsala were concluded to be of mainly geological origin, while contents of Cd, Cu, Zn, Pb and Hg seemed to have been impacted upon by mainly urban activities.

Introduction

The natural occurrence of trace metals in soils originates from the soil parent material, where the surface horizon contains metals that have been cycled through vegetation, atmospheric deposition and adsorption by soil organic matter (Alloway 1990). The soil profiles in urban environments have, however, seldom developed naturally but are instead constructed, with anthropogenic activities resulting in additional metal inputs to the soil (Thornton 1991). Berglund *et al.* (1994) found in a study on Stockholm soils that the metal content varied greatly between sampling sites and was independent of soil depth due to mixing, moving and back filling of soil masses, as well as 'clean' soil having been mixed with polluted soil. High spatial variation was also found in a study on urban soil metal contents in six European city parks (Madrid *et al.* submitted for publication).

Urban soils commonly receive a higher load of metals than corresponding rural soils, and because metals are rather immobile once they reach the soil, hazardous elements derived from industrial activities dating back to the beginning of the industrial revolution can still be found in the soil. The long-term input of metals to the soil can result in decreased buffering capacity of the soil and groundwater contamination. Contents can also be reached that have negative effects on human health upon repeated exposure (Brinkmann 1994). Children in particular are more susceptible to the negative health effects of metals due to their small body size, developing nervous system and common behaviour of putting dirty objects and hands in their mouths. For children up to the age of six, ingestion of soil represents a significant route of contaminant exposure due to this behaviour (Mielke & Reagan 1998). In a study on 2-year old children carried out in UK by Thornton *et al.* (1994), it was found that ingestion of dust as a result of hand-to-mouth behaviour accounted for upto 50% of a child's daily Pb intake. Acute health effects of metals are uncommon in the urban environment, but there are several subtle, chronic and long-term effects such as lowered IQ that are of great concern (Klaassen 1996).

The subject of metal contents in urban soil has received much attention in the past decade. Investigations on urban soil metals have for example been carried out in Stockholm (Berglund *et al.* 1994), Gothenburg (Rundquist & Johansson 2000), Oslo (Tijhuis *et al.* 2002), Jakobstad (Peltola & Åström 2003), Tallinn (Bityukova *et al.* 2000), Berlin (Birke & Rauch 2000), Seville (Madrid *et al.* 2002), Madrid (de Miguel *et al.* 1997) and Hong Kong (Li *et al.* 2001). Results from urban soil metal investigations have been used in city planning to identify pollution sources, locate polluted areas for remediation measures and to establish suitable grounds for new residential areas (Tijhuis *et al.* 2002; Peltola & Åström 2003). High natural metal contents in a region result in a decreased soil buffering capacity and a larger risk of exceeding guideline values. Information on a region's naturally high metal contents is therefore useful when establishing permissible pollution levels and evaluating current land use.

Many urban areas are today subject to remediation programmes due to high local soil metal contents, often caused by industrial activity. Background levels and guideline values have been established in many countries indicating the concentration of metals of natural origin and a maximum tolerable metal level, respectively. The Swedish Environmental Protection Agency has defined urban background levels as the natural soil metal content together with the normal load of anthropogenic metals (Petsonk & Sjölund 1997). The background value thereby includes diffuse anthropogenic metal inputs. However, the metal contents derived from natural sources can exceed the guideline values set up by authorities for contamination (Lax 2002). One example of negative health effects due to elevated, natural concentrations is the excess of As in drinking water in Bangladesh and West Bengal, India, which has put an estimated 25–75 million people at risk of arsenosis. Nepal, Vietnam, Taiwan and PR China also have arsenic contamination of groundwater (Ng *et al.* 2003). In the Guizhou Province of China, high natural contents of As and F have resulted in negative health effects for more than 10 million people (Finkelman *et al.* 2001). Arsenic, Cd and Ni are examples of metals that exceed the guideline values in some Swedish soils for geological reasons (Lax 2002).

The present study attempts to make a distinction between soil metal contents derived from natural sources and metal contents that are a result of anthropogenic activities. Soil samples were collected from playgrounds located in Uppsala City since children are more sensitive than adults to the negative health effects of soil metals. Forthcoming studies will investigate the bioavailability of soil metals to children with regard to particle sizes and availability inside the body. No previous studies have been carried out on soil metal contents in urban Uppsala. The current study is financed by the EU-project URBSOIL, which investigates urban soil parameters, including metals. Other than urban Uppsala, Aveiro (Portugal), Glasgow (Scotland), Ljubljana (Slovenia), Seville (Spain) and Torino (Italy) are participating in the project.

Study area

The city of Uppsala is Sweden's fourth largest town, covering an area of 100 km^2 and maintaining a population of around 136,500. It was founded in the 13th Century and developed into a religious and academic centre through the first university of the Nordic countries, which was founded in 1477 by the archbishop. In the second half of the 19th Century, several brickworks and milling industries were established and the city expanded geographically (Engström 2001). The brickworks resulted in large areas of the now built-up parts of the city being excavated and foreign soil being added to fill the quarries. In the beginning of the 20th Century, metal industries became the most important industry in Uppsala, followed by textile, food and chemical industries. During the second half of the same century, many industries moved from Uppsala and the city once again became more of an academic centre. A second university, the Swedish University of Agricultural Sciences, was established in 1977 (Lönnberg 2001). At present, Uppsala is mainly an academic city with approximately 37% of its population employed or enrolled at the two universities (Uppsala City Council 2004).

The bedrock in the Uppsala area was formed around 1880–1900 million years ago (Arnbom & Persson 2001) and is part of the Fennoscandian shield. Supracrustal rocks (supracrustal metasediments and metavolcanics of basic–acidic composition) form an elongated body just north of the city. South of the city, the supracrustal series is composed mainly of sedimentary gneiss with layers of basic tuff. There are also occurrences of quartz diorite, mica schist, uralite–porphyrite, gabbro and metabasite. Tectonic movements caused magma to rise towards the surface after the peak of the Svecofennian orogeny and this formed the Uppsala granite. It is grey basic granite with andesine and blue quartz as its main minerals. Secondary effects altered the supracrustal rocks into red, mainly intermediate to acidic granites, with quartz, microcline, oligoclase and biotite as their main constituents (Gretener 1994). The bedrock is exposed in some parts of the city due to scraping movements during the most recent deglaciation.

The geology of the Uppsala region has mainly been affected by the most recent ice age. Figure 1 illustrates the different layers of deposits in central Uppsala. The deglaciation process started about 8300 B.C. and lasted for approximately 170 years, leaving superficial deposits primarily composed of till. Exceptions are wave-washed bedrock outcrops, glacio-fluvial material deposited in the form of ridges or hills and fine-grained silts and clays accumulated in depressions. The till is in general sandy, with clay content of 1–4% and contains no or little concentrations of calcium carbonate. Illite, chlorite and vermiculite are the dominant minerals of the till (Gretener 1994). The till amounts to no great thickness in the urban area and is exposed mainly in connection with exposed bedrock. Glaciofluvial deposits have resulted in the Uppsala esker, a dominant feature of the city's landscape. It is ridge-shaped with a relief up to 40 m in the central part and runs in a north–south direction, consisting mainly of pebbles, gravels and sand, overlain by sand, silt and clay. During the retreat of the ice-front, fine-grained sediments in the form of glacial clay were deposited in depressions within large parts of Uppsala. The glacial clay is heavy and varved by the greater deposits during summer and less in winter. The colour is reddish brown from Fe hydroxide as well as crushed orthoceratite limestone from the Gulf of Bottnia (Lidén 1989). The clay content varies between 45 and 80% and the calcium carbonate content between 15 and 30%. According to Collini (1950), the summer varves contain high $CaCO_3$ contents, while carbonates are almost absent in the winter varves. Illite is the dominant mineral, with low varying contents of vermiculite, chlorite and kaolinite. The glacial clay is mostly exposed on the western side of the esker and is in large parts overlain by post-glacial clay, also dominated by illite (Lundin 1988). The post-glacial clay is usually between 0.5 and 3 m deep, but is found at 25 m depth in the city centre along the River Fyris. It is grey in colour, usually does not contain any calcium carbonate and may have a clay content of up to 60%. Apart from clay, gyttja clay is also present as a post-glacial deposit. The organic content of this clay varies between 2 and 30%, its clay content is about 40% and it has a thickness of 0.5–1.5 m (Gretener 1994). In the most central part of the city, the different clays can be upto 120 m in thickness (Lidén 1989). According to the FAO soil classification, most of the soils in Uppsala County are classified as Cambisols predominated by the Eutric and Dystric sub groups (Eriksson & Wiberg 1988).

According to Möller (1993), the Uppsala granite contains low contents of heavy metals while leptite contains Zn, Cu and small amounts of Cd. The greenstone has high background values of Cr, Ni and Co. According to Ek (1992), the soils of Uppsala County contain naturally elevated contents of As, Cd, Cu, Co, Cr, Mo, Ni, U and low contents of Hg, Pb and Se. The concentrations of V, W and Zn are in the same range as for the rest of the country. However, Ekelund *et al.* (1993) found in their study that W occurred at slightly elevated contents in the granite bedrock of Uppsala, resulting in elevated soil contents in the vicinity of exposed bedrock.

The main metal point sources located in Uppsala are the sewage treatment plant, the heat and

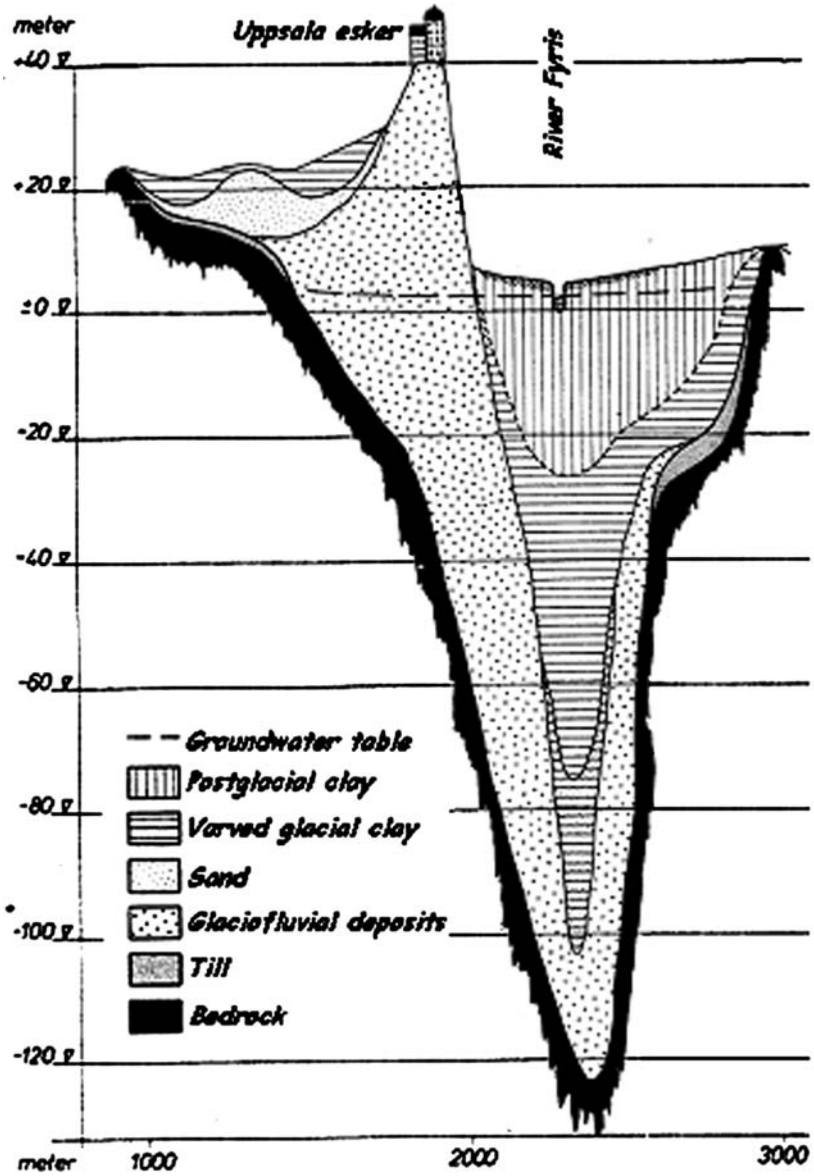

Fig. 1. East to west cross-section of Uppsala soil and bedrock. Twenty times exaggerated (Lundin 1988, revised by Lidén 1989).

energy plant, car washes and the airforce base. The heat and energy plants are the main sources of Hg, Pb, Cr, Cu, Ni, Zn and As. Important diffuse sources include traffic and long-range atmospheric deposition of metals (Stock 1996). Other than the heat and energy plants, a major source of Hg to the soils in Uppsala has been the crematorium, which up until 2000 released approximately 8.5 kg of mainly metallic Hg into the air annually. The release of Hg has today decreased to 0.5 kg annually (Örnestav, personal communication).

Materials and methods

Soil samples were collected at 25 sites around urban areas in Uppsala City. The locations are depicted in Figure 2. Three sampling points were selected at each site and composite samples consisting of five subsamples within 1 m^2 were sampled at each point. A stainless steel auger was used to a depth of 20 cm and the sample core was divided into depths of 0–5, 5–10 and 10–20 cm. The samples were collected from lawns where the

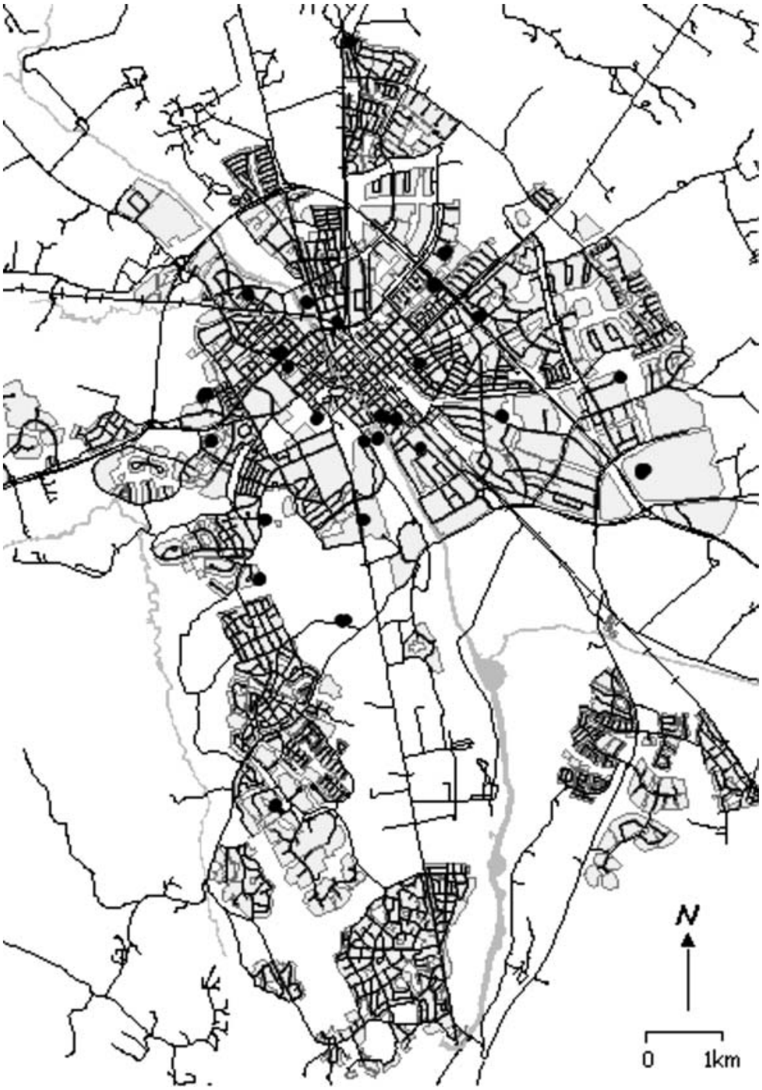

Fig. 2. Sampling sites in Uppsala City.

soil was exposed due to trampling. The sampling sites consisted of playgrounds at day-care centres and in public parks, where children frequently come in contact with the soil. The sampling was thereby not carried out according to a systematic spatial pattern; instead the sampled playgrounds were situated in areas of different land uses. The land use categories were industrial area, roadside, city centre, natural land and discontinued industrial land. Metal distribution in the city with regard to these landuses is reported in Ljung *et al.* (submitted for publication).

The samples were put in plastic bags and kept at 4 °C until preparation for analysis. The samples for analysis were dried at 40 °C, ground and sieved to pass through a 2 mm sieve.

Dry matter was determined by drying the samples at 105 °C overnight. The same samples were then put in a muffle furnace and ignited at 500 °C in order to get an estimate of the organic matter content. Soil pH was determined in H_2O and $CaCl_2$ (1:5) according to ISO 10 390 (2002). The two top layers, 0–5 and 5–10 cm of each sampling site, were mixed for the mechanical analyses, since the difference in texture between these layers is believed to be negligible. The mechanical analysis was performed using the pipette method (ISO 13 317–2 2001). The determinations described above were all carried out with the inclusion of reference samples from each of the cities participating in the URBSOIL project.

Aqua regia digestion was performed on all duplicated samples according to ISO 11 466 (2002). One blank and two reference samples were included in the digestion. The digestates were analysed for Al, As, Cd, Cr, Cu, Fe, Hg, Mn, Ni, Pb, W and Zn content using ICP-AES and/or ICP/MS-DRC. The aqua regia digestion extracts most of the potentially mobile metal fractions, but leaves the more resistant silicates undissolved (Peltola & Åström 2003).

Statistical treatment

Prior to further statistical evaluation, all parameters were tested for normal distribution by evaluating skewness and kurtosis. Organic matter content, pH and soil particle size all had a normal distribution and a paired *t*-test could therefore be performed. Frequency distributions of the metals showed that only Al, Fe, Mn and Cr had normal distributions. However, for the other elements normal distributions were obtained when outliers were excluded. In order to include all values in the statistical analysis, non-parametric statistical methods were used on the metal contents (median, Spearman Rank correlation, Mann–Whitney *U*-test). Reimann & Filzmoser (1999) evaluated common statistical methods and their suitability for use on data without a normal distribution. They found cluster analysis as one of the more suitable multivariate methods, and it was therefore used in this study. Minitab^{TM} statistical software release 13.31 was used.

Comparison with Gothenburg

In order to investigate the metals that may be present in urban Uppsala due to geological sources, a comparison was made with results from a similar investigation carried out in Gothenburg City by the Geological Survey of Sweden (Rundquist & Johansson 2000). Their study investigated the contents of several metals in mosses, plants, rural and urban sediment and till soils, as well as urban surface samples. Their data on urban surface samples collected in the 0–20 cm depth were used in the present study. The soil samples used in their study were sieved to 2 mm and digested with nitric acid (7 M), as compared to aqua regia used in the present study. Lax (2004) has performed a comparison on the dissolution of metals in aqua regia and HNO_3 (7 M). The study (unpublished) was based on 120 samples of till (C-horizon, < 0.06 mm) and showed that digestion with aqua regia is comparable to digestion with HNO_3 for As, Cd, Cu and Pb, while HNO_3 digestion dissolves less Fe, Mn, Ni and Zn by 12, 46, 17 and 16%, respectively.

Gothenburg is Sweden's second largest city, situated approximately 460 km southwest of Uppsala on the western coast. It has a population of 467,000, about 3.5 times larger than Uppsala. Gothenburg was founded as a centre for trade and shipping in the 17th Century and became Sweden's most important port for exporting goods in the 20th Century (Göteborgs City Council 2004). Gothenburg therefore has a different industrial history to Uppsala, with its mainly academic background. It was assumed in this study that elements found at significantly higher contents in Uppsala would indicate a geological rather than urban origin.

Results

General parameters are presented in Table 1. Most samples were around neutral to slightly alkaline in accordance with the calcareous nature of the post-glacial clay present in Uppsala (Lundin 1988). A few sites located in coniferous forest had slightly to moderately acid pH. The organic content was generally low. A paired *t*-test performed to identify differences in depth yielded a significant difference ($p < 0.05$) in particle size, pH and organic content between the top and bottom layer, with pH increasing with depth and organic content decreasing with depth. A predominance of the coarser fractions was observed in the 0–10 cm layer, while the finer fractions were more abundant in the 10–20 cm layer.

Minimum, maximum and median contents of the metals investigated are presented in Table 2. The elements Al, Cr, Mn, Fe and Zn showed a normal distribution throughout the profile, while Cd and Cu only showed a normal distribution in the 10–20 cm layer. The remaining elements all had skewed distributions due to outliers. Normal distributions were obtained for As, Cd and Cu when values from one site each were omitted, while extreme values of Hg were found throughout the profile at two sites. Elevated contents of Pb and W were found at several sites.

Table 1. Minimum, mean, maximum and standard error of the mean (SE) of general parameters in urban Uppsala ($n = 75$ for pH and LOI, $n = 25$ for particle size).

	0–5 cm				5–10 cm				10–20 cm			
	Min	Mean	Max	SE	Min	Mean	Max	SE	Min	Mean	Max	SE
pH H_2O	4.7	7.1	8.1	0.1	4.6	7.2	8.1	0.1	4.8	7.3	8.4	0.1
pH $CaCl_2$	3.9	6.6	7.5	0.1	3.8	6.7	7.5	0.1	4.0	6.8	7.7	0.1
LOI (%)	1.4	6.8	12.7	0.6	1.4	5.1	8.7	0.4	1.0	4.1	8.0	0.4
					0–10 cm				10–20 cm			
Clay					7.7	22.1	35.4	2.0	8.3	26.7	44.8	1.9
Silt					11.1	23.7	41.0	1.9	13.9	28.0	45.4	1.7
Fine sand					13.7	29.6	50.1	2.4	9.6	25.8	45.7	2.2
Coarse sand					6.0	16.7	31.8	1.8	1.4	13.9	35.7	1.7

Table 2. Minimum, median and maximum contents of metals in 0–5, 5–10 and 10–20 cm depths ($n = 75$).

	0–5 cm			5–10 cm			10–20 cm		
	Min	Med	Max	Min	Med	Max	Min	Med	Max
As (mg kg^{-1})	1.41	3.46	15.0	1.41	3.91	16.2	1.33	3.86	23.7
Al (%)	1.02	1.84	3.26	0.96	2.25	3.53	1.03	2.47	3.45
Cd (mg kg^{-1})	0.076	0.214	0.712	0.092	0.212	0.985	0.069	0.218	0.398
Cr (mg kg^{-1})	13.7	31.6	62.1	12.5	37.7	60.6	14.4	43.3	64.5
Cu (mg kg^{-1})	10.9	25.4	110	13.4	25.6	356	10.5	26.0	53.7
Fe (%)	1.56	2.49	3.79	1.33	2.76	4.07	1.36	3.03	4.11
Hg (mg kg^{-1})	n.d	0.139	3.66	n.d	0.146	5.41	n.d	0.130	1.11
Mn (mg kg^{-1})	199	494	833	162	526	940	145	573	968
Ni (mg kg^{-1})	7.22	18.5	39.1	6.22	21.1	56.6	7.31	23.2	42.5
Pb (mg kg^{-1})	8.53	25.5	358	8.76	24.6	163	9.53	26.4	160
W (mg kg^{-1})	0.149	0.346	0.984	0.152	0.350	2.57	0.118	0.345	1.09
Zn (mg kg^{-1})	44.8	84.0	149	37.8	90.4	245	27.4	98.6	191

A Mann–Whitney *U*-test was performed in order to evaluate differences in metal contents between the top layer and the bottom layer. The test showed that the bottom layer had slightly higher contents of As, Al, Cr, Fe, Mn and Ni ($p < 0.05$), while there was no difference between the medians for Cd, Cu, Hg, Pb, W and Zn. Of the former group of metals, all but Mn showed a strong significant correlation with the soil's clay content ($p < 0.05$). For the remaining elements, all but Hg correlated significantly with the clay content, but not very strongly ($r < 0.7$, $p < 0.05$). The correlation with the clay content was positive for all elements except W. Metal correlations with pH and organic content were negative, with only As and Fe correlating significantly ($p < 0.05$) with the organic content and Cd, Hg and Pb with pH.

The 10 and 90th percentile together with median values and maximum values for both Uppsala and Gothenburg are depicted in Figure 3. Most elements showed a higher median content in the Uppsala soils than in the Gothenburg soils. Median contents of both Cr and Ni were four-fold higher in the Uppsala samples, those of W seven-fold higher, and median contents of As, Cu and Zn were one to one-and-a-half times higher in Uppsala than in Gothenburg. The Cd contents were similar in both cities, while Gothenburg soils were enriched with Hg and Pb (1.4 and 1.5 times, respectively).

A cluster analysis was performed in order to group metals with closer similarities. The dendrogram in Figure 4 separates the analysed metals into two main groups. The cluster containing As, Al, Fe, Cr, Ni and Mn is most likely to have a common natural origin, while anthropogenic inputs to the soil have had a greater influence on the soil content of Cd, Cu, Zn, Pb and Hg. A greater similarity between metals depicts a stronger correlation.

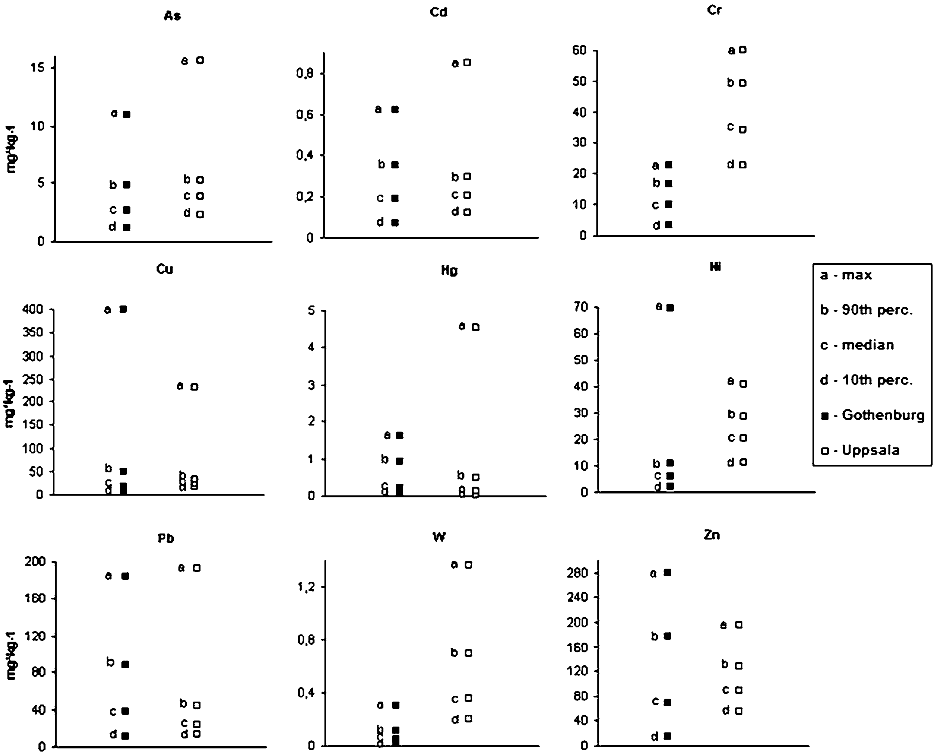

Fig. 3. Comparison between maximum (a), 90th percentile (b), median (c) and 10th percentile (d) of metal contents in Gothenburg (■) and Uppsala (□).

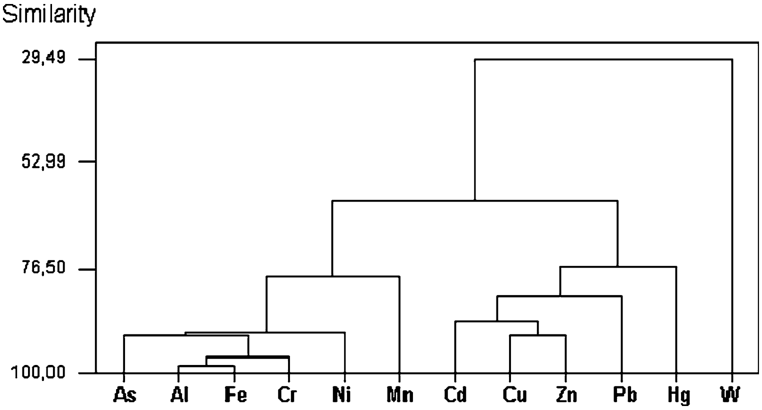

Fig. 4. Cluster analysis of metals, 0–20 cm ($n=75$, Linkage method: complete. Distance measure: correlation. Similarity shown in %) showing one cluster with elements of mainly natural origin (As, Al, Fe, Cr, Ni and Mn) and one cluster with metals of mainly anthropogenic origin (Cd, Cu, Zn, Pb and Hg).

Discussion

Information gathered from a geological map of Uppsala shows that most of the original soil of the city is clayey, with a few isolated spots of sand and silt (Lundin 1988). The relatively high sand content observed in the top layers of most sites indicates that soil material originates from elsewhere. This is in accordance with the common practice of removing the topsoil and replacing it with foreign material when constructing green areas, as well as the filling of quarries after the former brickworks in Uppsala. According to Selinus (personal communication) urban soils are commonly disturbed down to at least 1 m depth. The higher percentage of fine particles in the bottom layer is common in urban soils from splashing raindrops on bare ground, which disintegrates aggregates and washes very fine particles downwards in the soil profile (Craul 1985). The relatively high pH is in line with the calcareous soils of Uppsala and the common enrichment of carbonates in urban soils due to addition of calcium from de-icing agents and weathering of surrounding buildings. The organic content is low, a natural feature of Uppsala soils. The sampled sites were also affected by excessive trampling, resulting in scarce vegetation and low organic content, another characteristic for urban soils (Craul 1985).

In comparison with a study on agricultural soil in Uppsala County (Klang & Eriksson 1997) the median values for Cu, Cr and Pb in the current study were within the agricultural ranges, with Pb at the upper end and Cr in the lower end. Median contents of Ni and Zn were both found to be below the range, while Hg content was above. According to Selinus & Ek (1993) the soils of the Uppsala region have low contents of As, between 1 and 6 mg kg^{-1}. The median As content in the present study was within this range.

The results from the comparison between Gothenburg and Uppsala cities showed that only Hg and Pb was present at greater median contents in Gothenburg than in Uppsala, in spite of the larger size and industrial history of Gothenburg. Contents of As, Cd, Cu and Zn were found at similar or slightly higher contents in Uppsala. Peltola & Åström (2003) show that the size of a city and its number of inhabitants are not directly related to the soil metal content. Smaller cities often have industrial areas preserved closer to the city centre, while contaminated sites are often buried under concrete or removed in larger cities. In addition, Peltola & Åström (2003) found that the soil is not necessarily less contaminated in a small city, only that the contaminated areas are smaller.

The cluster analysis showed that the group with the closest similarities clustered As, Al, Fe, Cr, Ni and Mn, elements that are most likely to originate from natural/geological sources. The natural origins of Cr and Ni are supported by the finding of significantly higher contents of Cr and Ni in Uppsala as compared to Gothenburg. These elements are enriched in the greenstone of the area (Selinus 1997) and elevated in the soil due to the high clay content (Selinus & Ek 1993). Tungsten (W) was also found at a significantly higher content, suggesting a geological source, in line with the enrichment in the granite bedrock (Ekelund *et al.* 1993). Its separation from the other metals is most likely due to its differing chemical properties. The Cr content in Uppsala was within the range of the corresponding agricultural soil, further suggesting that the elevated presence of Cr in Uppsala is due to elevated natural contents rather than an anthropogenic source within the urban area. The urban soil content of As was also within the range of the region, which is low, indicating that the anthropogenic input is minor and the main source of As is geological. An explanation for the greater dissimilarity between Mn and the remaining elements was not found from the current literature on Uppsala soils and bedrock, but could be explained by additional anthropogenic sources. According to Reimann *et al.* (1998), Mn is present in several products common in the urban environment, for example as a replacement for Pb in unleaded petrol (Mielke *et al.* 2002). Leaded petrol has been banned in Sweden since 1995, and it can be assumed that the anthropogenic input of Mn to urban soil since then has increased.

According to Baize & Sterckeman (2001), the natural relationship between a soil's Fe content and contents of Cu, Co, Cr, Ni, Pb and Zn is linear. A soil's Fe content can therefore be used to distinguish between natural and anthropogenic inputs of the metals above (Huisman *et al.* 1997). A strong significant correlation was found between Fe and Cr as well as Fe and Ni ($p < 0.05$) further supporting the division pictured above.

The second group from the cluster analysis contained Cd, Cu, Zn, Pb and Hg, all elements that are common urban pollutants. Birke & Rauch (2000) conclude in a study on Berlin soils that these elements are common in the subsoil of industrial areas. Likewise, Cd, Pb and Zn were found accumulated in the topsoils of central Tallinn (Bityukova *et al.* 2000). Copper and Hg were not analysed in their study. Selinus & Ek (1993) report that contents of Cu and Zn are elevated in the Uppsala region compared to national background values due to the high clay content of the soil. Pb and Hg are also known to adsorb strongly to the finer particles of the soil. However, no correlation was found between clay content and Hg, while Cu, Zn and Pb only correlated weakly to the soil's clay content, suggesting that the anthropogenic sources of these metals influence the soil content more than the geological sources. The absence of a correlation between Fe and Cu, Pb and Zn further supports their anthropogenic origin. The closer similarity between Cu and Zn could be explained by a common, but minor natural source. The main sources of Cd, Cu, Zn and Pb in Uppsala are traffic and the heat and energy plants, with traffic being of more importance for the soil Pb content than for the contents of the other elements, which is the reason for the separation in the dendrogram. Similarly, the heat and energy plants are a source of Hg, but the soil input of Hg from the crematorium is of greater importance. According to the Gothenburg study, contents of Cd, Cu, Hg, Ni and Pb were concluded to be of anthropogenic origin, with Pb and Cu contents significantly elevated. The Ni content in Uppsala is discussed above, and the similar contents of the remaining elements in the two cities further support the assumption that their main source is also anthropogenic in Uppsala.

In a study on trace element origins in street dust carried out in Madrid by de Miguel *et al.* (1997), a similar division into groups of natural and urban origin was found. Of the elements investigated in the present study, de Miguel *et al.* (1997) found Cu, Zn, Pb and Cd to be most likely of urban origin while Mn, Fe and Al were of natural origin. Ni was believed to originate from both natural and anthropogenic sources. Similarly, in a study on Oslo soils by Tijhuis *et al.* (2002), Fe, Al, Cr, Ni and Mn were concluded to be of geological origin, with Mn having additional anthropogenic sources. Cd, Zn, Hg, Cu and Pb were believed to be of mainly anthropogenic origin.

Concluding remarks

The high sand content found at most sites suggests that the soil in urban Uppsala is of foreign origin. The lack of depth distribution for many parameters also indicates that the original soil has been disturbed. However, the agreement between enriched bedrock metal contents and urban soil metal contents implies that the foreign soil in urban Uppsala is derived from the surrounding rural area.

This study concluded that the parent material contributes to the relatively high contents of Cr, Ni and W in urban Uppsala. Soil contents of As, Al, Fe and Mn were also mainly derived from geological sources, although the Mn content has been influenced by anthropogenic sources to a greater extent since the abolition of leaded petrol in 1995, through the substitution of Mn for Pb in unleaded petrol. Contents of Cd, Cu, Zn, Pb and Hg are mainly derived from anthropogenic sources, with the Uppsala heat and energy plants as main sources. Traffic is another main source that particularly affects the Pb content of the soil, while the crematorium is a major source of Hg.

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References cited

Alloway BJ. 1990 *Heavy Metals in Soil*, Bishopbriggs Glasgow: Blackie and Son Ltd.

Arnbom JO, Persson L. 2001 *Bedrock Map 11I Uppsala NV, Scale 1:50 000, SGU serie Af 210*. Uppsala: Geological Survey of Sweden (in Swedish).

Baize D, Sterckeman T. 2001 Of the necessity of knowledge of the natural pedo-geochemical background content in the evaluation of the contamination of soil by trace elements. *Sci Total Environ* **264**, 127–139.

Berglund M, Fahlgren L, Freland M, Vahter M. 1994 *Metaller i mark i Stockholms innerstad och kranskomuner – förekomst och hälsorisker för barn*. IMM-rapport 2/94, Stockholm: Institute of Environmental Medicine, Karolinska Institute (in Swedish).

Birke M, Rauch U. 2000 Urban geochemistry: investigation in the Berlin metropolitan area. *Environ Geochem Health* **22**, 233–248.

Bityukova L, Shogenova A, Birke M. 2000 Urban geochemistry: a study of element distributions in the soils of Tallinn (Estonia). *Environ Geochem Health* **22**, 173–193.

Brinkmann R. 1994 Lead pollution in soils adjacent to homes in Tampa, Florida. *Environ Geochem Health* **16**(2), 59–64.

Collini B. 1950 On the mineralogical composition of Swedish quarternary clays. *Geologiska Föreningens i Stockholms Förhandlingar* **72**(2), 192–206in Swedish.

Craul PJ. 1985 Urban soils. In *Proceedings of the Fifth Conference on the Metropolitan Tree Improvement Alliance, May 23–24, 1985* University Park, Pennsylvania: The Pennsylvania State University.

de Miguel E, Llamas JF, Chacòn E, Berg T, Larssen S, Ròyset O, Vadset M. 1997 Origin and patterns of distribution of trace elements in street dust: unleaded petrol and urban lead. *Atmos Environ* **31**(17), 2733–2740.

Ek J. 1992 *Kommunalt miljökemiskt kontrollprogram för luft, mark och vatten – Del 2; biogeokemisk kartläggning av Uppsala kommun*. Rapport GRAP 2-1992. Research report, Geological Survey of Sweden (in Swedish).

Ekelund L, Nilsson C-A, Ressar H. 1993 *Biogeokemiska kartan – tungmetallhalter i bäckvattenväxter. Rapporter och meddelanden nr 75*. Uppsala: Geological Survey of Sweden (in Swedish).

Engström CJ. 2001 *Översiktsplan för Uppsala stad. Samrådshandling*, Del 1. Uppsala: Uppsala City Council (in Swedish).

Eriksson T, Wiberg M. 1988 *Soil Map of Sweden*. KSL, Box 6806, 113 86 Stockholm, Sweden.

Finkelmann RB, Skinner CW, Plumlee GS, Bunnell JE. 2001 *Medical Geology*, Geotimes 11.

Göteborgs City Council: 2004, http://www.goteborg.se.

Gretener B. 1994 *The River Fyris, A Study of Fluvial Transportation*. UNGI rapport nr 87. Doctoral Thesis, Institute of earth sciences, Uppsala University.

Huisman DJ, Vermeulen FJH, Baker J, Veldkamp A, Kroonenberg Klaver SB G Th. 1997 A geological interpretation of heavy metal concentrations in soils and sediments in the southern Netherlands. *J Geochem Explor* **56**, 163–174.

ISO 10 390. 2002 Soil Quality – Determination of pH, International Organisation for Standardisation.

ISO 11 466. 2002 Soil Quality – Extraction of trace elements soluble in aqua regia. International Organisation for Standardisation.

ISO 13 317-2. 2001 Determination of particle size distribution by gravitational liquid sedimentation methods – Part 2: Fixed pipette method, International Organisation for Standardisation.

Klaassen CD. 1996 *Casarett & Doull's Toxicology: The Basic Science of Poisons*, 5USA: McGraw Hill Companies Inc.

Klang E, Eriksson J. 1997 *Heavy Metals in Agricultural Soils in Uppsala County 1996*, Länsstyrelsens meddelandeserie 1997:17, Miljö- och fiskeenheten. Uppsala County Administration (Länsstyrelsen) (in Swedish).

Lax K. 2002 Bakgrundshalter av metaller i mark. In Wiklander G. ed. *Forskningsnytt om mark*. Reports in Forest Ecology and Forest Soils 84. Uppsala: Department of Forest Soils, SLU (in Swedish).

Lax K. 2004 Geologist at the Geological Survey of Sweden, Personal Communication, July 2, 2004.

Li X, Poon C, Liu PS. 2001 Heavy metal contamination of urban soil sand street dusts in Hong Kong. *Appl Geochem* **16**, 1361–1368.

Lidén E. 1989 *Uppland smälter fram ur inlandsisen*, Geological Survey of Sweden (in Swedish).

Lönnberg A. 2001 Kartläggning av nedlagd miljöfarlig verksamhet i centrala Uppsala. Diarienummer: 2000–2228. Uppsala: Environmental Protection Office, Uppsala City Council (in Swedish).

Lundin SE. 1988 *Engineering Geological Map of City of Uppsala*. Licentiate Thesis. Uppsala: Department of Quarternary Geology, Uppsala University.

Madrid L, Díaz-Barrientos E, Madrid F. 2002 Distribution of heavy metal contents of urban soils in parks of Seville. *Chemosphere* **49**, 1301–1308.

Mielke HW, Reagan PL. 1998 Soil is an important pathway of human lead exposure. *Environ Health Persp* **106**, 217–229.

Mielke HW, Gonzales CR, Powell E, Shah A, Mielke PW. 2002 Natural and anthropogenic processes that concentrate Mn in rural and urban environments of the lower Mississippi River Delta. *Environ Res Sec A* **90**, 157–168.

Minitab ^{TM} Statistical Software, release 13.31, version5.0 2195. Service Pack 4 Build 2195, Microsoft Windows 2000 Professional.

Möller H. 1993 *Description to the Quaternary Map, Uppsala NW. SGU Serie Ae 113*, Uppsala: Geological Survey of Sweden.

Ng JC, Wang J, Shraim A. 2003 A global health problem caused by arsenic from natural sources. *Chemosphere* **52**, 1353–1359.

Örnestav R. 2003 Employee at the Berthåga Crematorium, Uppsala, Personal Communication, 26 March 2003.

Peltola P, Åström M. 2003 Urban geochemistry: a multimedia and multielement survey of a small town in northern Europe. *Environ Geochem Health* **25**, 397–419.

Petsonk A, Sjölund G. 1997 *Bakgrundshalter i mark – halter av vissa metaller och organiska ämnen i jord i tätort och på landsbygd. Efterbehandling och sanering*. Rapport 4640. Stockholm: Swedish Environmental Protection Agency (in Swedish).

Reimann C, Äyräs M, Chekushin V, Bogatyrev I, Boyd R, Caritat P De, Dutter R, Finne TE, Halleraker JH, Jæger Ø, Kashulina G, Lehto O, Niskavaara H, Pavlov V, Räisänen ML, Strand T, Volden T. 1998 *Environmental Geochemical Atlas of the Central Barents Region*. Grytting, AS, Norway: Geological Survey of Norway, 369 p.

Reimann C, Filzmoser P. 1999 Normal and lognormal data distribution in geochemistry: death of a myth, Consequences for the statistical treatment of geochemical and environmental data. *Environ Geol* **39**(9), 1001–1014.

Rundquist P, Johansson P. 2000 *Göteborgsprojektet, geokemi över tungmetaller och organiska miljögifter,* Geochemical report. Geological Survey of Sweden (in Swedish).

Selinus O, Ek J. 1993 Kommunalt geokemiskt kontrollprogram för luft, mark och vatten, Slutrapport. Uppsala: Geological Survey of Sweden (in Swedish).

Selinus O. 1997 Hur är tungmetallerna spridda i Mälarområdet? In Metaller, Hälsa, Miljö, text updated 1997, Metallbiologisk Skriftserie 1, *Proceedings of the First Seminar on Metals, Health and Environment, Uppsala 1993*, Metallbiologiskt Centrum i Uppsala, pp. 9–20 (in Swedish).

Selinus O. 2004 Head of Geochemistry Department, Geological Survey of Sweden, Personal Communication, Feb 12, 2004.

Stock J. 1996 Metaller-förekomst, källor och spridningsvägar i Uppsala kommun. Survey Report, Environmental Protection Office, Uppsala City Council (in Swedish).

Thornton I. 1991 Metal contamination in urban areas, In: Bullock p. (eds.) Soils in the Urban Environment, University Press, Cambridge pp. 47–75.

Thornton I, Watt JM, Davies DJA, Hunt A, Cotter-Howells J, Johnson DL. 1994 Lead contamination of UK dusts and soils and implications for childhood exposure: an overview of the work of the environmental geochemistry research group, Imperial College, London, England 1981–1992. *Environ Geochem Health* **16**, 113.

Tijhuis L, Brattli B, Sæther OM. 2002 A geochemical survey of topsoil in the city of Oslo, Norway. *Environ Geochem Health* **24**, 67–94.

Uppsala City Council. 2004 Statistics for Uppsala Municipality.