Metals in Soil and Vegetation in the Sudbury Area (Survey 2000 and Additional Historic Data)

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Many people from the Ministry of the Environment contributed to the collection of the data that went into the production of this report. Prior to 1996, studies of the terrestrial environment in the Sudbury area were conducted by scientists from the Ministry's Northern Region, Sudbury District Office. From 1996 onward the responsibility for terrestrial monitoring province-wide was assumed by Phytotoxicology scientists of the Standards Development Branch, Ecological Standards and Toxicology Section. The scientists and technicians at the Ministry's Laboratory Services Branch analyzed the many thousands of samples collected from the Sudbury area over the years.

The principal author of this report is Laura Morra. Randy Jones prepared the maps. Project management was provided by George Crawford and Dave McLaughlin.

A special acknowledgment is owing to Bill McIlveen. Bill McIlveen prepared the first draft of this report, but retired from public service before the project was completed. Bill had a special fondness for the Sudbury area and his extensive personal and professional studies spanning more than two decades have contributed significantly to our current understanding of the impact of the mining industry on the terrestrial environment of the Sudbury basin. Good luck Bill, and thanks.

Purpose of This Report

This report has four specific objectives:

1) to publish the results of the Ministry's most recent soil and vegetation sampling programs in the Sudbury area;
2) to report some previously unreleased Ministry Sudbury soil and vegetation chemistry data and to clearly identify by reference previously published data;
3) to assess the soil and vegetation contaminant levels in the Sudbury area against existing Ministry environmental quality guidelines; and
4) to identify the need for further investigations and assessments in the Sudbury area.

The data summarized in this report spans the period 1971 to 2000. Some previously unreported data from 1971-1999, is included here to ensure all MOE data is available. Data from other historic Sudbury environmental investigations are referenced in this report, however they are stand-alone companion documents and are not discussed in detail in this report. To facilitate reading of this document, details regarding protocols on sampling methodology, preparation, and analyses have been referenced or provided as appendices. Technical reviewers can obtain these protocols from the reference documents.

All data in this report were obtained from samples collected from several Ministry surveys designed to evaluate impacts on the terrestrial environment of the historic and on-going base-metal smelting and refining operations within the Greater Sudbury area.

Data from annual collections of vegetation chemistry reflects changes in air quality over the last 30 years, whereas soil chemistry reflects how air contaminants have accumulated in soil in the Sudbury area over more than 100 years of mining, smelting, and refining activities. In the past, measurements of contaminants in vegetation were used by the Ministry as a measure of air quality, but these high historical concentrations do not reflect the improved environmental conditions that exist today. In contrast, the accumulation of contaminants in the soil is of significant current interest. The MOE is using these data as a planning tool to help determine where the important data gaps are and therefore where future soil sampling efforts should be focused. Much more soil sampling will be done over the next few years, both by the Ministry and by the major mining companies, to fill these knowledge gaps and refine our understanding of soil metal levels in the Sudbury area.

It is also important to realize that this report is not intended to provide an exhaustive interpretation of the implications of the vegetation and soil chemistry in the Sudbury area. Although it is obvious that historic vegetation damage and recent recovery has occurred in the Sudbury area and that soil metal levels are now elevated, it is important that more sampling be done to determine both the extent and severity of soil metal levels in the communities before a thorough evaluation of their potential effects can be undertaken. Although not the focus of this report, the data contained here as well as the data from essential additional sampling currently in progress will allow for an ecological and human health risk assessment to be conducted specifically for the Sudbury communities.

Executive Summary

Environmental impacts of historical emissions of sulphur dioxide and heavy metals from the Inco Ltd. and Falconbridge Ltd. smelters in Sudbury have been well documented. Local and provincial governments, university researchers, and industry have done extensive monitoring, assessment, and reporting on the environmental impacts on terrestrial and aquatic ecosystems.

This report summarizes the previously unreported extensive soil and vegetation chemistry data from the *Sudbury Regular Survey*, the *Sudbury Special Survey*, and the *Year 2000 Surface Soil Survey*. These surveys were conducted in the Greater Sudbury area by the Ministry of the Environment during the period 1971 to 2000. Additional details regarding these surveys are provided in the report.

The study concludes that extensive sampling of soil and vegetation has illustrated elevated levels of heavy metals (specifically nickel, copper, cobalt and to a lesser extent, selenium) and arsenic are common in the Sudbury area. They are particularly elevated in the vicinity of the three historic smelting centres of Copper Cliff, Coniston, and Falconbridge, as well as, the historic roast yards. Apart from the roast yards [11], the highest concentrations in soil consistently occur in the top-most layer of the soil, usually 0-20 centimetres in depth. This indicates air emissions are the source of the contamination. Even though many samples have been taken several times over the last 30 years, it is not possible with this data set alone to confidently identify contaminant trends over time due to changes in laboratory procedures, the uncertainty that precisely the same site was sampled, and the natural variability of these contaminants in soil.

Soil levels are compared to the Ministry's Guideline For Use at Contaminated Sites in Ontario (1996). The MOE soil clean-up *Guidelines* have been developed to provide guidance for cleaning up contaminated soil. The *Guidelines* are not legislated regulations. Also, the *Guidelines* are not action levels, in that exceeding the level does not automatically mean that a clean-up must be conducted. The *Guidelines* were prepared to help industrial property owners decide how to clean-up contaminated soil when property is sold and/or the land-use changes. The value of the *Guidelines* to the Sudbury area report is to provide triggers that may suggest the need for additional investigation or assessment of soil contamination.

This study also concludes that additional sampling is required to achieve five objectives:

1) determine the soil metal and arsenic levels in residential communities adjacent to the smelting centers;
2) determine the soil metal and arsenic levels in industrial lands adjacent to residential communities;
3) contribute to the development of an ecological and human health risk assessment for the Sudbury area communities;
4) determine if the natural background levels of these contaminants are higher in the Sudbury basin due to the presence of base metal ore bodies; and
5) determine the true geographic extent of the metal and arsenic atmospheric deposition, based on the natural background levels.

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I. INTRODUCTION

The impacts of historical emissions of sulphur dioxide and heavy metals from the Inco Ltd. and Falconbridge Ltd. smelters in the Sudbury area are well known [3, 5, 21, 23]. Extensive monitoring and assessment of the environmental impacts on terrestrial and aquatic ecosystems has been conducted by local and provincial governments, university researchers, and industry. Early MOE investigations, conducted by the former Northern Region Sudbury District Office, focused on the effects of sulphur dioxide on vegetation [6, 7, 10, 14]. The incidence of acute vegetation injury caused by this gas has declined [1, 9, 13, 16] and the benefits of reductions in sulphur emissions are evident in the extent of vegetation recovery in the Sudbury area. More recently, increasing emphasis has been placed on the accumulation of heavy metals in soil, particularly copper and nickel, and their associated environmental effects [2, 8, 11, 12, 17, 18, 20, 22, 25].

Since 1996, the Ecological Standards and Toxicology Section (formerly the Phytotoxicology Section) of the Standards Development Branch has been responsible for terrestrial environmental monitoring in the Sudbury area, with an emphasis on delineating the zone of soil contamination. Improvements in air quality, in conjunction with land reclamation efforts, have significantly improved the extent of vegetation recovery in the most severely impacted areas [3, 4, 21].

This report summarizes the previously unreported extensive soil and vegetation chemistry data from the Ministry's *Sudbury Regular Survey*, the *Sudbury Special Survey*, and the *Year 2000 Surface Soil Survey* that were conducted in the Greater Sudbury area during the period 1971 to 2000. Although some of the earlier vegetation data have been summarized in previously released MOE reports [18], this is the first time that unreported historic soil and vegetation data has been collated with the most recent data and evaluated to illustrate the regional distribution of contaminants in surface soil. These data form the basis of an understanding of the extent and severity of surface soil heavy metal contamination associated with the mining industries in Sudbury. In addition, the data and interpretation against the Ministry *Guideline*, provide essential guidance for where additional sampling and assessment is required.

Information relating to the roast yards that operated historically in the Sudbury area has been previously published in 1998 [11], and has not been incorporated into this report. In addition, this report does not include sporadic data from soil and/or vegetation sampling that was conducted in response to complaint investigations on private residential properties. Information collected on private residential properties is privileged to the property owner, and all complaint investigation reports have been completed and provided to the complainants.

II. FIELD INVESTIGATIONS

The soil and vegetation data discussed in this report originated from three integrated but separately structured surveys: 1) the *Sudbury Regular Survey*, 2) the *Sudbury Special Survey*, and 3) *Year 2000 Surface Soil Sampling.*

1) The *Sudbury Regular Survey* consisted of a set of 21 widely-distributed sample sites

(Appendix B - Figure 1). Monitoring activities in this project were periodically revised with respect to sampling frequency and species sampled. The locations of sample sites for the *Sudbury Regular Survey* reflect the program's original objective, which was (primarily) to monitor the impacts of gaseous pollutants (i.e., SO_2) emitted from the older smelter operations on sensitive species of vegetation in the Sudbury region. Therefore the sample sites tended to be spread over a large area. The monitoring was initiated in 1970 prior to the commissioning of the Inco superstack in 1973. Data resulting from this sampling program from 1970 to 1984 have been previously published [18], hence only the results from the 1999 sampling are presented in this report.

2) The *Sudbury Special Survey* was initiated in 1971, also before the superstack became operational. The sampling design followed a structured protocol whereby up to 92 sample sites were established along the cardinal compass directions at increasing distances from each of the three smelting centres of Copper Cliff, Coniston, and Falconbridge. Although the sample sites were focused on the three centres of production, some sites extended out to 30 km distance. None of the *Sudbury Special* data has been previously published, therefore all data is summarized in this report.

3) The *Year 2000 Surface Soil Survey* is the most recent work. The soil data from the *Sudbury Regular* and *Sudbury Special* surveys were combined to identify preliminary data gaps and served as the basis for the additional sampling at 103 sites, that was carried out in 2000.

During these on-going soil and vegetation surveys, the sample preparation method, the analytical methodologies, and the laboratory detection limits changed around 1984. These changes were a result of analytical equipment acquisition and implementation of improved laboratory quality control and assurance protocols by the MOE. More detailed information relating to changes in analytical precision, accuracy, reliability, reproducibility, validity, sensitivity and/or potential for errors is provided in Appendix D. Due to the change in sample preparation and improvements made to analytical methods and detection limits, data from the same site cannot be confidently compared over time. In addition, early sample sites did not benefit from the precision of geo-referencing technology available today and so subsequent samples may not have been collected from precisely the same sites, which further erodes the confidence of time-trend data. In consideration of these changes, it is believed that data presented within this report provides a reasonably accurate picture of current and historic soil contaminant conditions in the Sudbury area.

Following 1984, all processed samples were forwarded to the MOE Laboratory Services Branch where they were analyzed for aluminum(Al), barium (Ba), beryllium (Be), cadmium (Cd), calcium (Ca), chromium (Cr), cobalt (Co), copper (Cu), iron (Fe), lead (Pb), manganese (Mn), magnesium (Mg), molybdenum (Mo), nickel (Ni), strontium (Sr), vanadium (V), and zinc (Zn) using the MOE Laboratory Services Branch accredited analytical method E3073L1. Antimony (Sb), arsenic (As), and selenium (Se) were analyzed using the MOE Laboratory Services Branch accredited analytical method E3245L1. Nickel, copper, cobalt, selenium and arsenic were the elements of interest for analysis based on historic knowledge of the smelting industry and the contaminants that are produced during operation. Due to improvements in analytical equipment and procedures, results for more than 20 metals can be acquired simultaneously during the ICP-AES metals scan.

All data in this report are dry weight totals, that is, the maximum amount of each element that can be leached by the acid used by the laboratory to prepare the sample for analysis. Determining total concentrations in soil and vegetation samples is the Ministry's standard operating procedure. Contaminant speciation and bioavailability tests were not undertaken on the soil samples used in this report. When the proposed 2001 soil sampling programs are complete, and a better understanding of the extent of the soil metal levels in the Sudbury area is obtained, then selected samples will be submitted for speciation and bioavailability analysis.

Interpretation of the soil and vegetation chemistry was based on comparisons with data from the control locations at Blind River and Mattawa as well as with MOE guidelines. Vegetation data were compared with *Upper Limit of Normal* (ULN) Guidelines established in 1989 [19] (Appendix G). Soil data were compared with Tables A and F of the *Guidelines for Use at Contaminated Sites in Ontario,* established in 1997 [21] (Appendix E) or the *Ontario Typical Range* (OTR_{98}) established in 1993 [20] (Appendix F) where soil guidelines were not available. All results are reported as dry weight concentrations in µg/g (micrograms/gram, or ppm, parts per million).

The Table F criteria represent background soil concentrations obtained from an MOE province-wide parkland sampling program. Concentrations that exceed the Table F criteria are usually indicative of a pollution source. The Table A criteria are the concentrations that must be met when a contaminated property is cleaned up for the purpose of residential or parkland re-development. The Table A criteria are effects-based and were derived to protect both human and ecological health, whichever is potentially affected at the lowest concentration. For example, the current Table A criterion for lead is 200 µg/g which was set to protect children from the potentially harmful effects of long-term exposure to lead. The criterion for nickel is 150 µg/g, but this is set to protect sensitive plant species because plants are affected at lower soil nickel levels than it takes to affect human health. Table A criteria are not available for all chemical parameters, since for some elements there is insufficient scientific information available to establish effects-based values (e.g. strontium), or the element is considered non-toxic even at relatively high concentrations (e.g. iron), or the element is a plant nutrient (e.g. magnesium). A summary of the Table F, Table A, OTR_{98}, and ULN guidelines used in this report is provided in Appendix H.

A. Sudbury Regular Survey 1999

In July, 1999, Phytotoxicology scientists of the MOE Standards Development Branch, Ecological Standards and Toxicology Section, collected samples of soil and vegetation at the 21 previously established sample sites of the *Sudbury Regular Survey*. The location of these sample sites are illustrated in Figure 1 (Appendix B). Most of the sites were initially selected in 1970, with additional sites added in 1972 and 1973.

Soil, birch foliage, and grass forage were collected at each location in 1970, 1971, 1972, 1973, 1974, 1975, 1976, 1979, 1984, and 1999. Since 1993, standardized soil sampling procedures were utilized [15]. *Sudbury Regular Survey* data current to 1987 have been previously published [18], therefore, only the most recent data from soil sampling conducted in the summer of 1999 is included in this report.

B. Sudbury Special Survey 1971- 1997

The *Sudbury Special Survey* was initiated in 1971. In that year, soil, trembling aspen foliage, and forage grass was collected (as available) at 92 sample locations (Appendix C - Maps 1 and 2). The sample sites were located along transects on the cardinal compass directions from each of the three smelters operating at that time (Copper Cliff, Coniston, and Falconbridge). Some allowance was made for accessibility via the existing road network, but a number of sites were located in places that could only be reached by hiking overland. To the extent possible and practical, sample sites were positioned 0.5, 1, 2, 3, 4, 5, 10, 15, 20, and 25 miles from the smelters along the north, south, east, and west transects. Because of the relative positions of the smelters, the sample locations coincided along the east-west transect between Copper Cliff and Coniston, and along the north-south transect between Coniston and Falconbridge.

The sampling was repeated in 1976, 1981, 1992 and 1997. Over time, some sample sites were lost to changing lands use, such as construction of houses or other buildings associated with urbanization, road relocation, or closure of road or properties to public access. By 1997 the number of sample sites in the *Sudbury Special Survey* was reduced to 63.

Notably, vegetation was not available at all sites in 1971 but small trees and forage were sufficiently abundant at all sample sites in the more recent collections either because of land reclamation efforts or natural colonization of the bare sites over time. In 1971, soil was collected from 0 to 2.5 cm and from 5 to 10 cm. In subsequent years, the sampling was carried out at depth intervals of 0 to 5, 5 to 10, and 10 to 15 cm, which are now standard Phytotoxicology soil sampling protocols. Single samples were collected at each site in 1971. Sampling was conducted in triplicate in 1976 and 1981 and in duplicate in 1992 and 1997. Analysis of the samples included nickel, copper, cobalt, arsenic, iron, sulphur, selenium, and zinc in all years. Additional elements were available for analysis in later years due to improved analytical techniques.

Unlike the data from the *Sudbury Regular Survey*, the results from the *Sudbury Special Survey* have not been formally published in an MOE report. The *Sudbury Special* data was supplementary to the *Sudbury Regular* data, and although it added to the understanding of metal loadings in the Sudbury area it did not represent new or significant revelations. In addition, the *Sudbury Special* data was circulated among government, academic, and industrial organizations, was used in local environmental workshops and symposiums, and was an important data base for the Sudbury Land Reclamation Program.

C. Year 2000 Surface Soil Survey

In early 2000, data from the *Sudbury Regular* and *Sudbury Special* surveys were assessed to identify any geographic data gaps. Only the more recent data from sites that were accurately located were used for this preliminary exercise. While this assessment corroborated the pattern anticipated from general monitoring experience in the area and provided reasonable preliminary estimates of the contaminant distribution in soil, it also illustrated that some areas had relatively poor coverage and therefore areas where additional samples were needed.

In the summer of 2000, surface soil samples (0-5 cm) were collected at 103 additional sites in the Sudbury area (Appendix C - Maps 1 and 2). The sampling followed standard Phytotoxicology protocols [15] and the samples were analyzed for a suite of chemical elements that included nickel (Ni), copper (Cu), cobalt (Co), arsenic (As), cadmium (Cd), chromium (Cr), lead (Pb), molybdenum (Mo), selenium (Se), vanadium (V), zinc (Zn), calcium (Ca), magnesium (Mg), iron (Fe), aluminum (Al), manganese (Mn), sulphur (S), strontium (Sr), beryllium (Be), and barium (Ba).

Due to the presence of an extensive naturally occurring nickel and copper ore bodies in the Sudbury area, some questions have been raised about the applicability of the Table F guideline for nickel (43 µg/g) and copper (85 µg/g) in the Sudbury area. One approach to addressing this question has been to utilize the nickel results from previous sampling stations for which there is soil profile data, 0-5, 5-10, 10-15 cm depths, to determine the background concentrations for the area. Assuming the contamination is from areal deposition, the concentrations will be highest in the surface soil and will decrease with depth. Therefore, the depth soil results should more closely represent natural background nickel and copper concentration.

III. ANALYTICAL RESULTS

A. Sudbury Regular Survey 1999

The analytical results for the 1999 *Sudbury Regular Survey* are summarized in Tables 1 to 3. The results for soil (Table 1), birch foliage (Table 2), and grass forage (Table 3) samples are briefly discussed below.

i) <u>Results of Soil Analysis</u>

In 1999, only 8 of 20 elements, those being arsenic, cadmium, cobalt, chromium, copper, nickel, selenium, and strontium, exceeded the MOE Table F background-based soil guidelines (Table 1). Of these eight elements, only nickel, copper, cobalt, and arsenic exceeded the MOE Table A effects-based soil guidelines at the sites closest to Copper Cliff and Falconbridge, specifically Garson, Skead, Ramsey Lake, and Tilton Lake. In general, the higher metal concentrations were found in samples from the top of the soil profile, which is consistent with aerial deposition. The highest nickel (1,000 µg/g) and copper (980 µg/g) concentrations were found at Ramsey Lake, while the highest cobalt (57 µg/g) and arsenic (32 µg/g) concentrations were found at Tilton Lake and Skead, respectively. For the most part, the pattern of soil metal contamination below 5 cm followed the surface concentration pattern; however, the nickel concentration at Callum in 1999 was slightly elevated throughout the depth profile. Soils at this location are particularly sandy (near a sand and gravel pit). The lack of organic matter and clay particles, combined with the relatively large pore size of sand, provide very little chemical or mechanical binding power so that contaminants move more readily through sandy soil.

Calcium concentrations in Sudbury area soils were low but within the normal concentration range for northern Ontario soils. The lowest mean soil calcium concentrations occurred in soils from Skead and Chiniguichi Lake area. The significance of these sites includes the fact that Skead was historically one of the sites most heavily impacted by SO_2 and calcium would have been more readily leached from the soil by inputs of sulphuric acid. Chiniguichi is a considerable distance from Sudbury but it is located directly downwind of the smelters, the soils are known to be poorly buffered, and lakes in that area have become acidic.

Despite high SO_2 emissions over the past six decades, little evidence of sulphur accumulation in soil was observed in 1999. Sulphur is more reactive in the soil than most of the heavy metals and a lower concentration of sulphur in the soil may be due to the implementation of SO_2 abatement programs. However, the unit of measurement for sulphur in soil is percent and not parts per million, so the ability to measure relatively minor changes is compromised. The only site in 1999 with a soil sulphur concentration above the OTR_{98} was Ramsey Lake, which is likely due to the frequent SO_2 fumigations that were measured historically in the Sudbury Basin.

The concentrations of the remaining elements (aluminum, barium, beryllium, calcium, iron, lead, magnesium, manganese, molybdenum, strontium, vanadium, and zinc) did not exceed background levels. This was anticipated because the smelters at Sudbury are not known to emit these elements in substantial quantities.

ii) Results of Vegetation Analysis

In 1999, only 7 of 20 elements, those being cadmium, chlorine, iron, magnesium, nickel, selenium, and zinc, exceeded the Upper Limit of Normal (ULN) guidelines for unwashed rural tree foliage (Table 2). In 1999, only 3 of 20 elements, those being chlorine, iron, and nickel, exceeded the ULN guidelines for unwashed grass forage (Table 3).

Only one site in 1999 had elevated iron (520 µg/g) in both tree foliage and grass forage (Tables 2 and 3). These concentrations occurred at Temagami, which is an area known for its iron deposits.

Four sites had nickel concentrations above the ULN guideline of 30 µg/g in paper birch foliage (Table 2). These included Garson, Rayside, Skead, and Tilton Lake. The highest concentration was 50 µg/g nickel at Garson. Only one forage collection site, Tilton Lake (27 µg/g) had a nickel concentration above the ULN guideline of 25 µg/g in grass forage (Table 3).

The zinc concentrations measured in paper birch foliage in 1999 exceeded the ULN guidelines at 18 of the 21 sites sampled (Table 2). Birch species are known to accumulate zinc to higher levels than most other species growing in the same soils. No obvious distribution pattern relative to the Sudbury area smelters was noted, and the smelters are not known to emit zinc in substantial amounts. The zinc concentrations in birch foliage measured at over half of the sites were higher in 1999 than in any of the previous years. There is not a readily apparent explanation for this, but the trend did not extend to the grass forage samples (Table 3).

Despite the general publicity and magnitude of sulphur dioxide emissions from the Sudbury area smelters, the number of sites where excessive levels of sulphur occur in vegetation is fairly limited, based on the present survey. However, like soil, the concentrations of sulphur are measured in percent (as opposed to µg/g for other elements) and substantial quantities of the element must be absorbed by the foliage before significant changes in the foliage chemistry become apparent. Also, the process of development of sulphur dioxide-induced injury to plant foliage does not necessarily require the uptake of large amounts of SO_2 into the tissues. None of the sites sampled in 1999 had sulphur concentrations above the ULN guideline.

For the remaining elements, the measured concentrations indicate background levels.This would be anticipated because the Sudbury smelters are not known to emit these elements in substantial quantities. The elements which had strictly background concentrations in tree foliage include aluminum, arsenic, barium, boron, beryllium, calcium, cobalt, chromium, iron, potassium, lead, manganese, molybdenum, strontium, sulphur, and vanadium. In addition to these elements, cadmium, magnesium, selenium, and zinc also had background concentrations in grass forage.

B. Sudbury Special Survey 1971 - 1997

Because of the large amount of data obtained from the *Sudbury Special Survey* (Tables 4 to 27), it is not practical to discuss the analytical data in detail. The following summaries are provided mainly as general observations and patterns. See Maps 1 and 2 for soil and vegetation sampling locations (Appendix C).

i) Results of Soil Analysis

The concentrations of elements measured in the soil samples are summarized in Tables 4 to 16.

Arsenic

The highest arsenic concentration measured was 510 µg/g at Site 23 (1 mile north of Falconbridge) in 1976 (Table 4), although by 1992 the soil arsenic level at the same sample site had fallen to 57µg/g. Other sites with arsenic concentrations greater than 200 µg/g included Sites 22 (290 µg/g), 24 (350 µg/g), 29 (470 µg/g), and 30 (350 µg/g), all of which are located within 3 km of the Falconbridge smelter. By comparison, the maximum arsenic concentration near Copper Cliff was 290 µg/g found at Site 97 in 1971 (1 mile west of the smelter). The pattern of background-based Table F guideline exceedences (17 µg/g) follows closely the pattern of effects-based Table A guideline exceedences due to the small difference between the two guidelines. About half of the sites exceeded the background-based Table F guideline of 17 µg/g in 1971.

Surface soils had higher concentrations of arsenic than did the samples from the lower soil profiles.

Cobalt

The maximum cobalt concentration of 788 µg/g was found at Site 99 in 1971 (3 miles west of Copper Cliff) with concentrations decreasing with depth (Table 5). Nearly one third of the sites sampled exceeded the cobalt Table F guideline of 21 µg/g. Fewer sites exceeded the cobalt Table A guideline of 40 µg/g (Table 5). The highest concentrations of cobalt occurred near Copper Cliff, although soil cobalt levels were proportionately elevated within three miles of Falconbridge.

Copper

Only eleven of 92 sites did not exceed the Table F (85 µg/g) guideline at some point between 1971 and 1997 (Table 6). The Table A guideline was exceeded at approximately half of the sites sampled in 1997. In 1997, the highest copper concentration measured was 2,800 µg/g (Site 96, 0.5 miles west of Copper Cliff). The other sites where copper exceeded 1,000 µg/g were Site 72 (0.5 miles east of Copper Cliff, 1,600 µg/g, 1997), Site 97 (1 mile west of Copper Cliff; 1,900 µg/g, 10-15 cm, 1997), and Site 106 (0.5 miles south of Copper Cliff; 1,300 µg/g, 0-5 cm, 1992).

The highest copper concentrations were encountered in the surface horizon and decreased with depth. Sites within about 5 km of Copper Cliff had copper concentrations considerably greater than sample sites elsewhere in the Sudbury area.

Iron

Five sites of 92 sampled had soil with iron concentrations above the OTR_{98} guideline in one or more years (Table 7). Two of these 5 sites had single year/depth exceedences, while the remaining three sites had multiple depth exceedences. At Site 97, located 1 mile west of Copper Cliff, the surface soil iron level exceeded the background guideline in 1971, 1986, 1992, and 1997. The high concentrations were particularly evident throughout the soil profile in the two most recent collections.

Nickel

A large proportion of the soil samples collected for the *Sudbury Special Study* contained nickel in concentrations above both the Table F and Table A guidelines (Table 8). In 1997, every surface soil site except two (Sites 35 and 70) exceeded the Table F guideline of 43 µg/g. The majority of these sites also exceeded the Table A guideline of 150 µg/g. In earlier years, the frequency of exceedences were lower. The highest nickel concentrations were found in the surface soil and decreased with depth.

The highest nickel concentrations were measured in 1997 with a maximum concentration of 2,300 µg/g occurring at Station 72 (0.5 miles east of Copper Cliff). The most conspicuous soil nickel contamination was observed in close proximity to the Copper Cliff smelter.

Selenium

Selenium concentrations in soil exceeded the Table A guideline of 10 µg/g at two sites (Table 9); these were Sites 96 and 97 (0.5 and 1 mile west of Copper Cliff, respectively) between 1986 and 1997. Surface soil (0-5 cm) at this site had selenium concentrations ranging from 11 to 33 µg/g, with the highest concentration being found in 1986. Sub-surface concentrations exceeded the Table A guideline in 1986 and 1997 but in the other years, the concentrations were much lower indicating considerable heterogeneity of the soil. The highest concentration at Site 97 was found at the 10-15 cm level in 1997.

A pattern in selenium concentrations is noted when the data above background but below the Table A guideline from sites surrounding Copper Cliff are reviewed. There are three sets of contiguous sites leading from Copper Cliff to Lively (Sites 96 to 100), Belanger (Sites 87 to 91) and Sudbury (Sites 72, 74 and 75) respectively that roughly follow the transportation system. This suggests that the use of waste materials or spent ore from tailings may have been used in the construction or maintenance of these roads and rights of way and are a contribution to the overall distribution of this metal, and possibly others, within the local environment.

Sulphur

In 1971, approximately half of the surface soils exceeded the OTR_{98} guideline (Table 10). Neither Table A nor Table F guidelines have been developed for sulphur. The maximum concentration of 1.7 % sulphur was measured at Site 97 (1 mile west of Copper Cliff) in 1986. That site had elevated sulphur concentration throughout the soil profile fairly consistently over the study period.

Zinc

The zinc concentrations measured in the soil exceeded the Table F guideline of 160 µg/g at five sites (Table 11). These included Sites 46, 59, 63, 66, and 87. There is no consistent pattern of elevated zinc in soil in relation to the three smelters.

Aluminum

The aluminum concentrations measured in the soil exceeded the OTR_{98} guideline of 30,000 µg/g aluminum (neither Table A nor Table F guidelines have been developed for aluminum) at two locations (Table 12). These included Sites 62 and 89. There is no consistent pattern of elevated aluminum in soil in relation to the three smelters.

Cadmium

The cadmium concentrations measured in soil exceeded the Table F guideline of 1.0 µg/g at 22 of 92 sites (Table 12). No sample sites exceeded the Table A effects-based guidelines.

Calcium

No sample sites exceeded the OTR_{98} guideline of 55,000 µg/g calcium (Table 13). Neither Table A nor Table F guidelines have been developed for calcium because this element is a major plant nutrient.

Lead

The lead concentrations measured in soil exceeded the Table F guideline of 120 µg/g at 5 of 92 sites sampled (Table 14). These included Sites 22, 87, 95, 101, and 113. Four of these sites exceeded the Table A effects based guideline of 200 µg/g, with the highest concentration (1,000 µg/g) occurring at Site 87 (5-10 cm, 1986). Four of the five sites are within the vicinity of the Copper Cliff smelter.

Magnesium

The magnesium concentrations measured in the soil exceeded the OTR_{98} guideline of 20,000 µg/g at one site, Site 37 (neither Table A nor Table F guidelines have been developed for magnesium)(Table 15). Although this site is located within 1 mile of the Falconbridge smelter, the value only slightly exceeded the OTR_{98} guideline and no consistent concentration gradient was evident relative to the three smelters.

Other Elements

In 1997, soil samples were also analyzed for barium, beryllium, manganese, molybdenum, strontium, and vanadium (Table 16). Exceedences occurred at only five sites. Site 44 had a molybdenum concentration (4.2 µg/g) above the Table F guideline of 2.5 µg/g, Site 63 had chromium concentrations (72 to 74 µg/g) above the Table F guideline of 71 µg/g, Site 97 had both barium and chromium above Table F guidelines of 210 µg/g and 71 µg/g, respectively, and Sites 102 and 103 had chromium concentrations above the Table F guideline. All other metals were not elevated above background, which was anticipated because the smelters at Sudbury are not known to emit these elements in substantive quantities.

ii) <u>Results of Vegetation Analysis</u>

The concentrations of chemicals measured in the vegetation samples are summarized in Tables 17 to 27.

Arsenic
Elevated levels of arsenic in vegetation were found to be much more prevalent in trembling aspen foliage than in grass forage (Table 17). In part, the differences between species may be related to the respective guidelines (2 µg/g arsenic for tree foliage and 8 µg/g arsenic for forage). The highest arsenic concentrations (12 µg/g in aspen, 20 µg/g in forage) occurred at Site 31, located 2 miles northeast of the Falconbridge smelter in 1976, and Site 29, located 0.5 miles northeast of Falconbridge in 1976, respectively.

Cobalt
The concentrations of cobalt in vegetation were conspicuously greater in trembling aspen foliage than in grass forage samples (Table 18). It must be noted that there are different guidelines for tree foliage and for grass forage. The maximum concentration of cobalt in aspen foliage was 17 µg/g (Site 82, about 10 miles east of Copper Cliff) in 1971 and in grass forage was 12.7 µg/g (Site 29, 0.5 miles northeast of Falconbridge) in 1976.

Copper
The concentrations of copper in vegetation were greater in trembling aspen foliage than in grass forage samples (Table 19). The highest copper concentrations found in aspen was 360 µg/g in aspen (Site 95, 20 miles north of Copper Cliff) and 220 µg/g in forage (Site 96, 0.5 miles west of Copper Cliff). Both high concentrations occurred in 1976. The two high values were notably higher than most of the other concentrations, even at these same locations in other years.

Iron
The concentrations of iron in the vegetation samples ranged widely (Table 20). The iron concentrations were most frequently elevated in the 1971 and 1976 collections. The highest concentrations measured were 5,500 µg/g in aspen and 3,200 µg/g in forage in 1981; both at Site 114, 25 miles south of Copper Cliff.

Nickel
Nickel concentrations in vegetation frequently exceeded the ULN guideline (Table 21). The highest nickel concentrations were 340 µg/g and 240 µg/g, respectively, in aspen and forage. Both high levels occurred in 1976. The aspen sample was collected 2 miles east of Coniston (Site 64) while the forage was collected 1 mile south of Copper Cliff (Site 107).

Selenium
Samples were not analyzed for selenium in 1971 (Table 22). The highest selenium concentration was found in aspen (5.3 µg/g) at Site 71 (about 25 miles east of Coniston) and in forage (4.1 µg/g) at Site 107 (1 mile south of Copper Cliff). Both of these occurred in 1976.

Sulphur
As might be anticipated following the commissioning of the superstack in 1972, the concentrations of sulphur in both aspen foliage and forage declined steadily with time until there were no exceedences in 1997 (Table 23). Forage concentrations exceeded the sulphur guideline of 0.5% at only 6 locations, all in 1971.

Zinc
Zinc is known to accumulate naturally in the foliage of some species, notably poplars, willow, and birch. No guideline specific to these species has been developed, however, the zinc concentrations observed in tree foliage in the Sudbury area were consistent with typical background levels encountered elsewhere in the province. Four samples of grass forage had zinc levels in excess of the 100 µg/g ULN guideline for forage (Table 24). These few exceedences did not appear to be related to the smelters.

Aluminum, Cadmium, Calcium, Lead, and Magnesium
Vegetation data for aluminum, cadmium, and calcium are summarized in Table 25 while lead and magnesium data are summarized in Table 26. For the duration of the *Sudbury Special Survey*, no vegetation samples had aluminum, cadmium, lead, or magnesium concentrations above the ULN guidelines for unwashed tree foliage and grass forage. These results are expected, since the smelters at Sudbury are not known to emit these elements in substantial quantities.

Other Elements
In 1997, vegetation samples were also analyzed for barium, beryllium, boron, chlorine, chromium, potassium, manganese, molybdenum, strontium, and vanadium (Table 27). Of these elements, only foliar chlorine concentrations exceeded the ULN guideline of 0.15%. These results are anticipated because the smelters at Sudbury are not known to emit these elements in substantial quantities.

C. Year 2000 Surface Soil Survey

i) Results of Soil Analysis

The analytical results for the soil samples collected in 2000 are summarized in Table 28. Soil levels for the following 10 metals in all 103 samples never exceeded their respective background levels and are discussed no further in this survey: aluminum, barium, beryllium, calcium, chromium, magnesium, manganese, vanadium, zinc and strontium.

Six other metals including iron, molybdenum, lead, cadmium, cobalt and selenium occasionally and sporadically exceed either their respective Table F (background) or OTR_{98} values. Iron exceeds the OTR_{98} at Site 370 and 393 with 36,000 and 45,000 µg/g respectively . Molybdenum exceeds the Table F background value at Site 393 with 3.6 µg/g. Lead exceeds the Table F background value at only two sites, Site 358 with 140 µg/g and Site 389 with 160 µg/g. Cadmium marginally exceeds its background value at five sites (337, 341, 351, 353,and 382). The data set for selenium is incomplete due to an error in ordering tests from the analytical laboratory. Available selenium data indicates that it exceeds background only at 8 of 103 sites. Cobalt exceeds its background level at 8 of 103 sites in this study with the highest value of 36 µg/g observed at Site 411, west of Coniston.

Soil nickel, copper and arsenic concentrations exceeded their Table F guidelines at most sites, and exceeded their respective Table A guidelines to varying degrees and frequencies. Each of these is discussed in more detail below. It is important to note that in all cases the effects-based Table A guideline for these three metals and arsenic is for the protection of sensitive plants.

Nickel

Nickel is the most widely dispersed metal in soil with respect to elevations above the provincial background (43 µg/g). The 43 µg/g guideline is exceeded from about Espanola on the west to nearly Hagar on the east, a distance of about 110 km in the east-west direction. The area above background extends a similar distance north to south. The distribution pattern is quite complex, with several areas extending from the three main smelting centres of Copper Cliff, Falconbridge, and Coniston.

Ninety four of the 103 sampling sites have nickel levels that exceed both the background (43 µg/g) and effects based (150 µg/g) guideline for nickel. Of these, 45 sites exceed the effects based number. Most of the data shows a localized and higer concentration of nickel at sites clustered around the three sources.

Sites 358, 359 and 360 (520, 250 and 260 µg/g) respectively are all located to the north and west of Falconbridge. These same sites are identified as elevated with other metals as well as nickel in the historic data.

Sites 362 through 374 are clustered around the vicinity of Copper Cliff and values that exceed the effects based guideline here range from a high of 690 µg/g to a low of 170 µg/g with the higher values closer to Copper Cliff.

Sites 408 through 437 (excluding Sites 410 and 411) are roughly clustered around Coniston. Values that exceed the effects based guideline here range from a high of 480 µg/g to a low of 180 µg/g. Again, there is trend towards a gradual decrease in levels with increased distance from Coniston.

Sites 337, 338, 339 and 341 (520, 25, 330 and 210 µg/g respectively) along with Sites 410 and 411 (270 and 980 µg/g respectively) present a different picture, with most concentrations marginally above background and two well above effect based guideline. These sampling sites tend to follow the highway corridor running into and out of the City of Sudbury, in one case north/ south in the other case east/ west. This may suggest the use of tailings material or waste ore in road construction. This same phenomenon was also observed for selenium in the Sudbury Special 1971-1997 survey data around Copper Cliff.

A single location greater than 43 µg/g nickel is identified to the east of Sudbury at Site 18 near Sturgeon Falls. However, this is driven by a single sample point. It is unlikely that this marginally elevated nickel concentration reflects generally elevated soil nickel levels in the Sturgeon Falls area. Because some sample sites between Sturgeon Falls and Sudbury have lower soil nickel levels, it is unlikely that the marginally elevated level at Site 18 is related to the Sudbury mining industries.

Copper

Copper levels exceed background at a total of 71 sites (70% of all sites) including 26 sites (25% of all sites) that also exceed the Table A effects based guideline. Except for two isolated samples that produced elevated copper results (one to the west and the other to the south), the area of elevated soil copper concentrations above the Table F background-based guideline of 85 µg/g is fairly well defined. This area extends from Whitefish on the west to approximately Lake Ashigami on the east, a distance of about 60 km. The north-south distance is similar, extending north of Capreol to Lake Nepewasi in the northeast and the east end of Lake Penage in the southwest.

Concentrations of elevated copper in soil occurred most consistently in the vicinity of Copper Cliff (Sites 360, 362, 363, 364 with levels of 330, 450, 390 and 280 µg/g respectively). There also appear to be two small areas above 500 µg/g copper near each of the Coniston (Sites 405, and 414 at 600 and 670 µg/g respectively) and Falconbridge (Sites 358 and 359 with 740 and 260 µg/g respectively) smelters. The Falconbridge Site 358 had the one of the highest observed copper concentration in this study.

Arsenic

Arsenic is observed to exceed its background and effects based guideline at a total of 19 of 103 sites, including 15 sites that exceed the effects-based guideline

The highest arsenic levels are observed in the vicinity of Falconbridge at Sites 358 and 359 with levels of 130 and 70 µg/g respectively. Sites 413 and 414 with levels of 25 and 37 µg/g respectively are situated to the west and south of Falconbridge suggesting an overall increase in soil arsenic burden in the general area caused by the smelter. The fact that these sites are also identified as having elevated levels of nickel and copper is considered additional evidence of a localized effect from the smelter.

Sites 360 and 362 at 25 and 22 µg/g respectively are also marginally above the Table A guideline. There is the potential that these sites in combination with sites and observations reported in the earlier studies (*Sudbury Special and Sudbury Regular*) and influenced by the Coniston and Copper Cliff smelters respectively.

Sites 370, 371, 376 and 393 with levels of 73, 21, 37 and 28 µg/g respectively are the next highest levels found. However there does not seem to be any pattern in these sites or the concentrations other than their locations south and west of Copper Cliff, suggesting an overall increase in soil burden in the general area caused by the smelter.

ii) <u>Background Nickel Concentrations In Sudbury Area Soil</u>

The most recent depth soil data from the *Sudbury Regular Survey*, and the *Sudbury Special Survey* were pooled to create a data base of 108 sample sites utilized in estimating the background nickel concentration in soil for the Sudbury area (see table below). A summary of the number of stations that fall within four ranges of nickel below 43 µg/g at the three sample depths is given in the following table. It is clear that even at 5 to 10 cm there are significantly more stations below the 43 µg/g Table F background value for nickel in soil than at 0 to 5 cm. The number of stations below 43 µg/g at the three depths, and a consistent pattern of lower soil nickel levels at depth, suggests that the Table F value of 43 µg/g nickel is a reasonable estimate of background for the Sudbury area.

Number of the Sampling Stations that Fall Within the Four Ranges of Nickel Concentration at the Three Sample Depths.

Nickel Range	Soil Depth		
	0 to 5 cm	5 to 10 cm	10 to 15 cm
<20 µg/g	2	9	7
20 to 29.9 µg/g	6	17	23
30 to 39.9 µg/g	5	12	14
40 to 42.9 µg/g	0	2	3
Total <43 µg/g	13	40	47

SUMMARY AND DISCUSSION

The MOE has been monitoring the terrestrial environment in the Sudbury area since 1970. Extensive sampling of soil, aspen and paper birch foliage, and grass forage has illustrated that elevated levels of heavy metals (specifically nickel, copper, and cobalt) and arsenic are common in the Sudbury area, and are particularly elevated in the vicinity of the three historic smelting and refining centers of Copper Cliff, Coniston, and Falconbridge. The highest concentrations in soil consistently occur in the upper horizons, indicating that the source of the contamination is atmospheric deposition. Even though many sites have been sampled several times over the last 30 years, it is not possible to confidently identify contaminant time trends due to changes in laboratory procedures, the uncertainty that precisely the same site was sampled, and the natural variability of these contaminants in the terrestrial environment. The exception is sulphur in vegetation, which has declined subsequent to the construction of the Inco superstack and with reductions in SO_2 emissions legislated by the MOE Countdown Acid Rain Program, which was completed in 1985. Elevated metal levels in vegetation are expected to continue as long as the contaminants are present in the soil and potentially available to be taken up by plants through their root systems.

The soil contaminant data illustrate that the highest soil metal levels are likely to occur in the urban communities close to the three industrial centers of Copper Cliff, Falconbridge, and Coniston. Because the emphasis in the past has been on defining the extent of the atmospheric deposition (i.e., the "footprint", how far it goes) the majority of the samples were collected at distance, and the urban areas of the City of Greater Sudbury were under-sampled. Additional sampling is required in the Sudbury urban area to further characterize soil contaminant levels.

The MOE Table A effects-based soil guidelines for nickel, copper, cobalt, and arsenic are generic values intended to be used anywhere in the province. The generic soil guidelines are based on the principal of protecting the most sensitive receptor. In setting these guidelines the Ministry reviewed the scientific literature for each contaminant and determined the lowest observable effect level (LOEL) for the most sensitive plants, animals, and aquatic organisms and the no observable effect level (NOEL) for human health. The lowest value was then selected as the generic guideline. For nickel, copper, cobalt, and arsenic the most sensitive receptors are plants: specifically, plants are injured at soil concentrations lower than those observed to affect animals, aquatic organisms, or people. Furthermore, not all plants would be injured at soil levels above the generic guideline, because there is a very broad range in plant sensitivity to soil contaminant concentrations. Therefore, the MOE Table A effects-based generic guidelines for nickel, copper, cobalt, and arsenic are based on the ***potential*** for injury to sensitive plant species. Soil concentrations above the Table A guidelines do not imply that plant injury ***will*** occur, but rather that it ***may*** occur if the most sensitive plant species are present and the soil characteristics are such that the contaminant is bioavailable (can be taken up from the soil by plant roots).

Soil contaminant concentrations close to the Sudbury smelters have been shown to be phytotoxic, and steps to counter the metal toxicity in the soil were required to establish vegetation in some areas remediated by the Sudbury Land Reclamation Program. Recently, substantial new plant growth, particularly paper birch, has occurred in some previously severely impacted areas at sites that did not receive soil amendments as part of the Sudbury Land Reclamation Program. Paper birch is very sensitive to SO_2 and the re-establishment of paper birch in these areas is a result of the reduction in the frequency of injurious ground level SO_2 fumigations. However, even in the absence of SO_2 fumigations the birch seedlings could not have become established on these sites if the soil metal levels were directly phytotoxic. Therefore, even though large areas of Sudbury exceed the Ministry Table A effects-based generic soil guidelines it is clear that air quality and not soil metal levels was the main factor limiting the natural re-establishment of vegetation. For the Sudbury area, soil metal levels substantially above the Table A guidelines are required before phytotoxicity occurs in local species of vegetation.

Recent health studies conducted in Wawa [24], Deloro [27], and Balmertown [26] found no measurable health impacts associated with soil arsenic levels in urban residential areas in the range of 500 to 2,000 µg/g. The highest soil arsenic level found in Sudbury to date is 510 µg/g in 1976. However, sampling of the same site in subsequent years could not reproduce that high value. The most recent soil arsenic level for that site is 57 µg/g, obtained in 1992. The maximum soil arsenic level obtained during the most recent and most extensive sampling in Sudbury, conducted between 1997 and 2000, was 130 µg/g, and relatively few sites exceeded the 20 µg/g MOE guideline. Although these other community studies contribute significantly to the understanding of how environmental contaminants may affect human health, they are site specific, meaning they are conducted using environmental conditions and multimedia assessments specific to their host community and their conclusions are valid only for that specific community.

In reviewing the extensive soil data base developed for the Sudbury area the ministry concludes that additional sampling and action is warranted. Especially in Sudbury's residential and publically-accessible urban green space, and communities adjacent to the three smelting centers of Copper Cliff, Coniston, and Falconbridge. Therefore the Ministry has developed a work plan to fill these important knowledge gaps.

- ❏ Over the summer and fall of 2001 the two industries will be collecting surface soil in remote areas around the Sudbury basin in an attempt to 1) confirm the local background concentrations for the contaminants of concern, if different from the Ministry's Table F guideline, and 2) having defined true local background, accurately determine the spacial extent of the heavy metal and arsenic deposition associated with their mining and smelting activities.

- ❏ Over the same time period, the companies will also be characterizing the soil contaminant status of their land holdings in areas where they exist adjacent to residential communities.

- ❏ During the summer 2001 the Ministry will collect surface soil samples from all schools and commercial day care centers in Sudbury.

- ❏ In the late summer and fall of 2001 the Ministry will sample soil and vegetable garden produce from a representative number of residential properties in the communities of Copper Cliff, Coniston, and Falconbridge.

- ❏ Throughout the summer and fall of 2001, the Ministry will sample blueberries, other wild berries, and berries from commercial farms in areas of suspected elevated soil levels.

- ❑ In the fall of 2001 the Ministry will sample surface soil from representative residential properties and major public parks in Sudbury.

The data obtained from the Ministry and industry 2001 sampling programs will be developed, prepared and distributed as public reports. It is possible that the data from the 2001 studies may identify the need for additional soil sampling in 2002. Nonetheless, the soil information obtained from the 2001 sampling program, in conjunction with the data from this report and the extensive existing Sudbury environmental data base, form the essential building blocks upon which an ecological and human health risk assessment for impacted communities in the City of Greater Sudbury, will be developed.

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