SUDBURY AREA RISK ASSESSMENT

VOLUME III – CHAPTER 3.0

OBJECTIVE #1: EVALUATE THE EXTENT TO WHICH COC ARE PREVENTING THE RECOVERY OF REGIONALLY REPRESENTATIVE, SELF-SUSTAINING TERRESTRIAL PLANT COMMUNITIES

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3.0 EVALUATING OBJECTIVE NO. 1

3.1 Introduction

This chapter addresses Objective #1 of the ERA, which is to evaluate the extent to which the COC are preventing the recovery of regionally representative, self-sustaining terrestrial plant communities in the Sudbury region. This is a key objective of the Sudbury ERA, as it dovetails with the re-greening and reclamation activities that have been ongoing in the Sudbury area for the past three decades. The regreening initiatives and programs were described in some detail in Chapter 4 of Volume I in this series of reports. While considerable progress has been made on the "re-greening" of the Sudbury landscape, some barriers remain; significant portions of the region have not recovered, or have not recovered to what is considered to be their full ecological potential. In addition, biodiversity in some of the reclaimed areas remains low compared with a natural forest ecosystem.

Therefore, it is the goal of this objective of the ERA to determine the role that COC from the smelters have in inhibiting recovery of the vegetation, and to identify if other causal factors are involved. This information can then be used to help guide future reclamation activities. In addition, the data collected from this objective will be applied to the broader Sudbury area using a combination of satellite and remote sensing photo interpretation to help identify which areas remain impacted and require consideration for remediation.

In risk assessment literature-derived values are often used to predict the toxic effect of metals on soil organisms including plants. However, there were three primary environmental variables/conditions in the Sudbury area that rendered the use of literature values insufficient to address this Objective:

1. Metal mixtures are present in Sudbury soils;
2. Sudbury soils have a low soil pH (which affects the toxicity of metals); and
3. The effects of conditions 1 and 2 to plant communities relevant to Sudbury are not fully documented.

Ecological communities are an aggregation of populations consisting of all plant, animal and microbial populations that occur in the same time and place and that interact physically, chemically and/or behaviourally. Although the community itself is what the risk managers ultimately aim to protect, it is not possible to study all components and, therefore, functional groups must be selected. It is not possible or desirable to perform toxicity testing on all species that exist, so representative species must be selected. Doyle et al. (2003) suggested that plants and soil dwelling organisms might be more at risk to atmospheric emissions from smelters than wildlife.

It is a challenge to determine whether an ecosystem is impaired, and to what extent. The complexity of direct and indirect interactions between physical, biological and chemical components with varying temporal and spatial scales requires the use of multiple assessment approaches, with consequent need to integrate the diverse data collected (Burton et al., 2002b). To answer Objective #1 and to address the Sudbury specific conditions noted above, it was determined that a combined field and laboratory program was necessary to collect the data required to identify those environmental factors or variables that may be inhibiting ecosystem recovery. A weight-of-evidence approach (WOE) was utilized in which a variety of data were collected to produce four distinct “lines of evidence” (LOE). WOE approaches reported in the literature vary broadly. No standard approach exists and no accepted guideline exists to describe how a WOE process should be conducted. Most users of the WOE term are simply implying that more than one line of evidence (LOE) is being used with a best professional judgment (BPJ) of harm or risk. This approach reduces the uncertainty of relying on any single measure of effect or exposure. One basic premise of the WOE approach is that if most of the assessment results suggest impairment, then there is a greater likelihood that there truly is ecosystem impairment; conversely, if most of the assessment results suggest no impairment, then this is most likely the case.

Weighting or integrating multiple LOE into a conclusion does not remove uncertainty. Rather, it should provide a sound, transparent process for reducing uncertainty by integrating the best available scientific information available at the time (Burton et al, 2002).

To address Objective #1, detailed data for each LOE were obtained from 22 characterized sites across the Sudbury area. Each of these LOE was evaluated independently to determine impact at each site. Next, the interactions between the LOE were evaluated using statistical techniques. Finally, the LOE were integrated using a WOE approach to determine whether the concentrations of metals in the soil were impeding recovery of a self-sustaining forest system.

It should be recognized that a great deal of effort for this Objective was expended to determine: a) if there were ecosystem impacts within the study area; b) what the relative magnitude of the effect was; and c) what the causative factors were. In this regard, it is more similar to a retrospective risk assessment, compared to a more predictive risk assessment approach used for Objectives 2, 3 and 4.

3.1.1 Navigating This Chapter

The main body of Chapter 3 provides a comprehensive overview of the field methods, analysis, results, site ranking and integration of the LOE used to address Objective #1. Efforts have been made to make the process as transparent as possible by providing all collected data and associated documentation. Because of the large volume of data collected and the number of laboratory and data reports associated with each LOE, the details are provided in sub-appendices to Appendix G of this report. The appendices and sub-appendices are provided electronically on CD at the back of this binder. The main challenge of incorporating all the data involved in this study was to create a document that was both informative and readable. The balance was struck by providing a summary of the data and steps involved in the process of addressing Objective #1 within the text, with all associated detailed information provided in the appendices. Therefore, to fully comprehend the decision making process, and to follow the associated steps taken to reach the Objective #1 conclusions, the interested reader must go beyond the scope of this chapter and read the associated appendices and sub-appendices. Four of the sub-appendices (GD through GG) are the test site ranking reports for each LOE. These four reports are presented in hard copy in Appendix G contained at the end of this report, and are useful for interpreting the rationale behind the LOE site ranking (Step 1).

3.2 Overview of Study Approach

This section provides a brief overview of the steps and approaches that are described in greater detail in the remainder of the chapter.

3.2.1 General Overview

The effectiveness and accuracy of any WOE approach is heavily dependent on five factors (Burton et al., 2002a):

- The quality of the data;
- The quality of the study design;
- The expertise of the principal investigators;
- The severity of the impairment (greater is easier to detect); and
- A matching of objectives and data.

Each of these factors was considered in the approach developed by the SARA Group to address Objective #1. Four types of data, or LOE, were collected:

- Physical and chemical soil characterization;
- Toxicity testing with terrestrial species in the laboratory;
- A plant community assessment; and
- An assessment of decomposition using *in situ* litter bags.

Detailed data and samples for each LOE were gathered from 22 study sites (18 test sites, 3 reference sites and 1 historically limed and re-greened site) across the Sudbury area during an intensive field and laboratory program conducted during 2004 and 2005. The sequence of steps involved in site selection, site characterization and data collection for each LOE is illustrated in Figure 3-1.

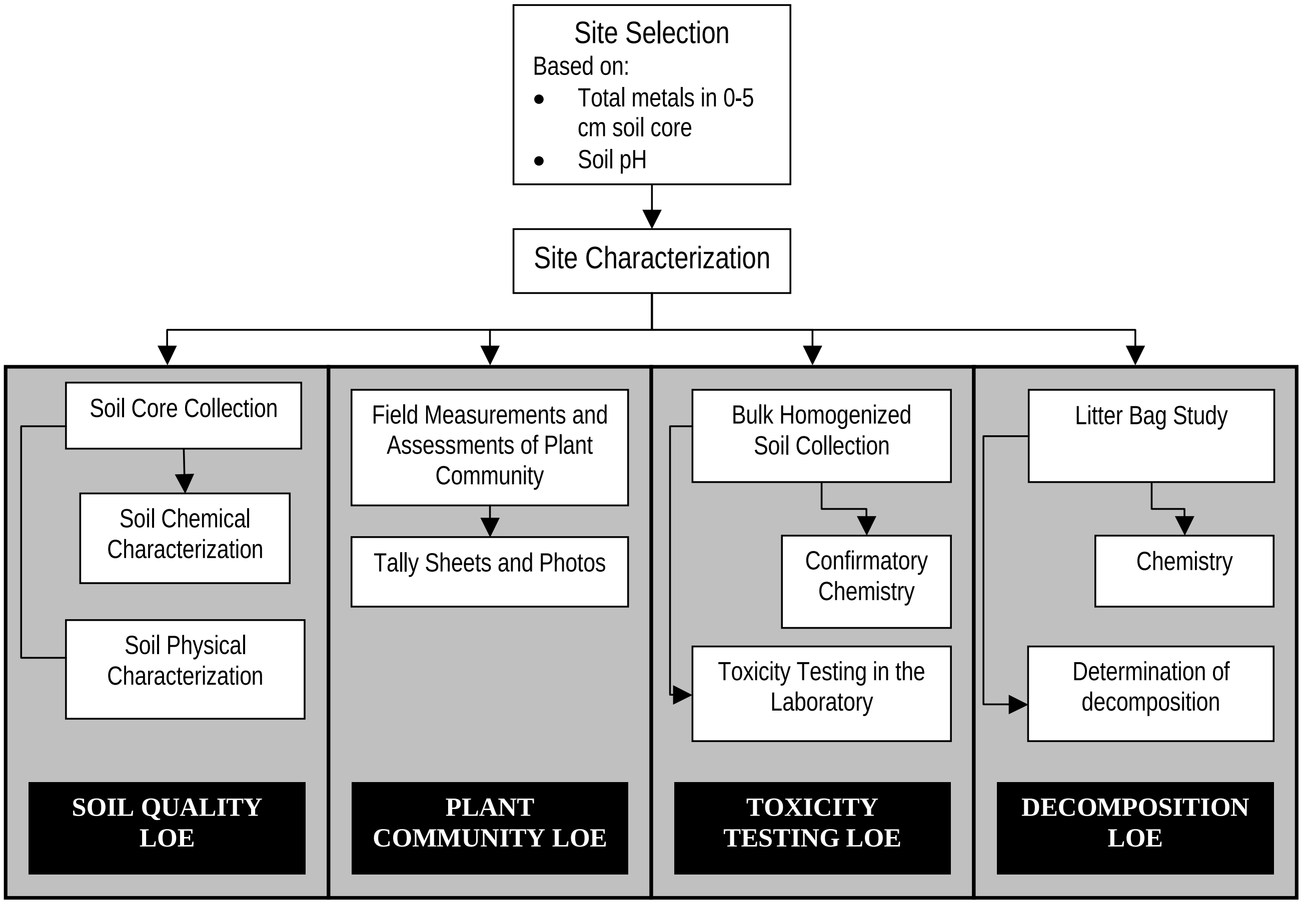

Figure 3-1 Overview of Studies at Field Sites for Each Line of Evidence (LOE)

The chronology of events at each study site is shown in Figure 3-2. The "test" sites represented locations containing a range of soil metal concentrations and conditions along transects associated with the three smelters: Copper Cliff, Falconbridge and Coniston. The "limed site" refers to a site on the Coniston transect (CON-07) which has undergone historic liming and replanting as part of the re-greening operations. CON-07 is adjacent to one of the test sites and was included in the study to assess the efficacy of the re-greening measures taken thus far. The three reference sites were selected for comparative purposes where the concentrations of COC were near or below the MOE Table 'F" background criteria levels (MOE, 1997) and the sites were representative of northeastern Ontario forest community conditions.

Lines of Evidence

For each of the LOE, a ranking approach was developed to assign a level of impact to each of the measured variables, and then to each site. The ranking approach was largely based upon comparing the test sites to the reference sites and used a consensus-based process including discussion with various experts in each relevant field. A final site ranking was given to each site by combining the ranks of the individual LOE. Each LOE was weighted differently depending upon a variety of factors, such as ecological significance and the uncertainty related to the LOE. All of the LOE were evaluated separately and then integrated to determine whether there was concurrence between the various LOE. Concurrence between the LOE was examined to determine whether the COC were likely causing any observed impairment. Using a WOE approach of this kind gives greater weight to endpoint agreement. Lack of concurrence does not necessarily mean one LOE is inaccurate; rather, that situation may simply reflect the complexity of the system.

Table 3.1 summarizes the list of variables and types of data collected for each LOE. Overall, several hundred measurements were taken, counted or analyzed at each site and used to quantify over 70 parameters.

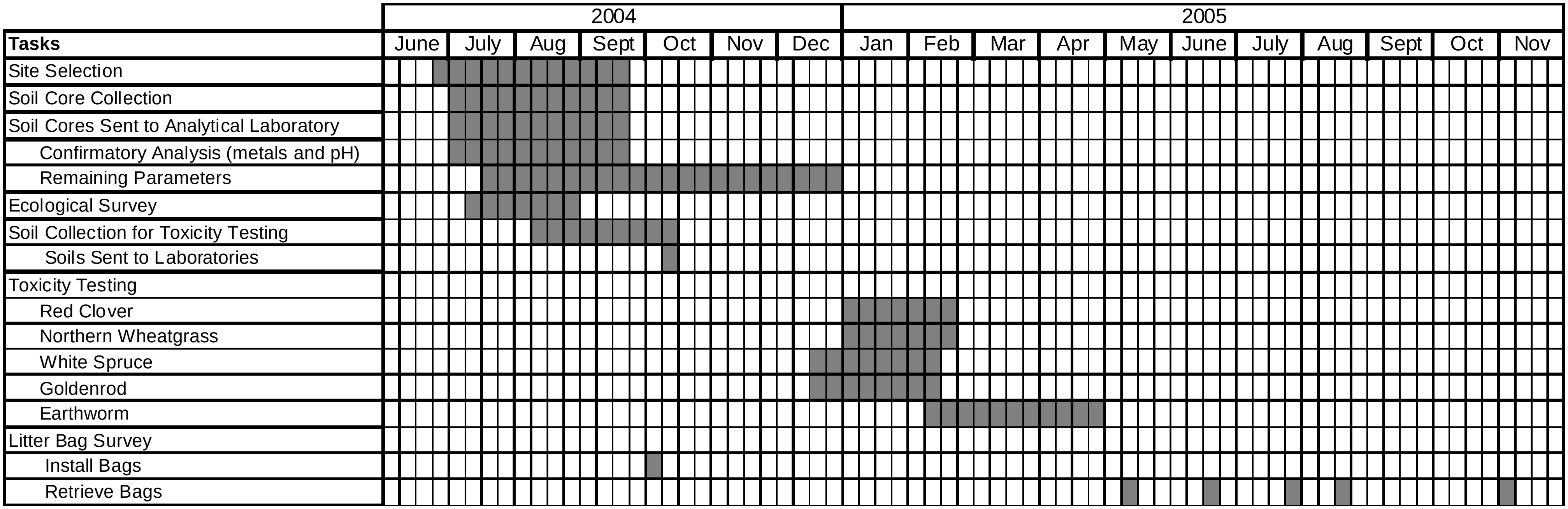

Figure 3-2 **Sequence of Events for Each Line of Evidence (LOE) for the 2004-2005 Field and Laboratory Studies**

Table 3.1 Summary of Data Collected for Each Line of Evidence for the 2004-2005 Field and Laboratory Study

Physical and Chemical Soil Characterization			Plant Community Assessment		Soil Toxicity Testing			Decomposition
Category		**Parameter**	**Tallies**	**Parameter**	**Category**	**Species**	**Parameter**	**Parameter**
Soil development		Pedon Classification	Broad Plant Inventory	Trees	Tree	White Spruce	root length	Rate of Decomposition
		Particle Size		Tall shrubs			root mass	
		Bulk Density		Low shrubs			shoot length	
Chemical	Metals	Total metals (HNO_3 extraction)		Herbs			shoot mass	
		Water leach (Plant available fraction)		Graminoids	Monocot	Northern Wheatgrass	root length	
	pH and Conductivity	pH in water		Pteridophytes			root mass	
		pH ($CaCl_2$)		Bryophytes			shoot length	
		Electrical conductivity		Lichens			shoot mass	
	Organic Matter	Carbon	Percent Cover	% Vegetation cover	Dicot	Red Clover and Goldenrod	root length	
		Total Nitrogen		% Ground cover			root mass	
		Total Sulphur	Tree and Tall Shrub Assessment	Species present			shoot length	
	Soil Exchange Complex Chemistry	CEC		% Cover			shoot mass	
		Potassium		Average height	Invertebrate*	Earthworm	# juveniles	
		Sodium		Growth form			mass of juveniles	
		Calcium		# Snags				
		Magnesium		Diameter				
		Manganese		% Mortality and dieback				
	Fertility	Nitrogen	Coarse Woody Material	Species				
		Phosphorous		Length				
		Potassium		Diameter				
		Nitrate/Nitrite		Degree of decomposition				
		Sulphur	Ecosite Classification	Terrain				
		Avail. Iron		% Slope				
		Avail. Manganese		Soil depth				
		Ammonium		Soil texture				
		Avail. Magnesium		% Bedrock				
				Dominant understory				
				Dominant overstory				
				% Canopy cover				

*Invertebrate results were not used in the final site ranking. Earthworm results are presented in Appendix GF10.

The process of data evaluation and integration followed a three-step procedure:

- Step 1: the information from each LOE at every site was evaluated separately, and the four LOE were then integrated to determine a final impact ranking for each site.
- Step 2: the interactions between LOE were examined; specifically, whether soil physical and chemical characteristics—including metals—were co-related to the other three LOE.
- Step 3: the environmental factors most likely related to the observed impacts at the test sites were examined through statistical analysis.

Site Selection

The total metal concentrations and the pH of the soil were the primary criteria used to guide site selection. These two factors are of vital importance, but because they were built into the selection of the sites, they were not considered during Step 1. During the individual LOE ranking, efforts were made to keep the study team evaluators from knowing the metal concentrations at the sites. Each LOE was evaluated "blindly" so that the metal levels would not prejudice the outcome. For example, knowing that a site had a high copper or nickel concentration may have biased the interpretation of the plant community assessment results. It is acknowledged that the experts evaluating each LOE were also involved in the study design and implementation, so were familiar with the sites. In an effort to keep the process as unbiased as possible, all data were presented to the experts without revealing the site identification number. In the process described below, soil metal concentrations were not considered during Step 1, but were considered in Steps 2 and 3.

3.2.2 Step 1: Evaluation of Individual LOE

Data were collected for each LOE at each site. Each LOE was evaluated and ranked at each site relative to reference site conditions, or to other criteria developed for a particular measured variable. This evaluation was completed independent of the metal concentrations of the soil and knowledge of the soil. The following procedure was applied to evaluate each of the LOE at each site:

- Evaluation of LOE information at the reference sites:
  - Establish whether the reference site conditions were indicative of a "typical" northern Ontario site.
  - Determine whether the reference sites were similar.

- Compare the LOE information from each test site to the reference sites:
    - Use a ranking system based on parameters and criteria appropriate to each LOE to determine an impact ranking for each criterion.
- Establish an overall rank for each LOE by integrating the ranks of the individual criteria.

The scoring system consisted of three possible ranks:

Rank	**Description**
Green	Low to Not Impacted
Yellow	Moderately Impacted
Red	Severely Impacted

Each rank was assigned a colour code (green, yellow, red) to help evaluate and illustrate trends in the data. At the completion of Step 1, each site had a rank for each separate LOE (four ranks in total). A final overall site ranking was assigned by integrating the individual LOE ranks.

3.2.3 Step 2: Evaluation of Interactions between the LOE

Independent of the conclusions found at the end of Step 1, the data from each LOE were compared to each other using statistical techniques. The aim of this evaluation was to determine whether the various LOE were related to each other. Two statistical approaches were used:

1. Multiple linear regression analyses were used to determine if there was a relationship between soil chemical parameters and soil toxicity (Section 3.12).

2. A canonical correspondence analysis (CCA) was used to determine whether there was a relationship between the soil chemistry parameters, the plant community at the site and decomposition endpoints (Section 3.12).

In order to complete these analyses, cluster and grouping techniques were employed to reduce the measurement variables to a manageable number, and the amount of covariance among the variables. As a result, super variables were created and then used in the comparison (Section 3.12).

3.2.4 Step 3: Determine Whether Metals in Soil are the Most Likely Cause of Impairment

To determine whether metals were the most likely cause of observed impairment, all of the sites were identified by colour according to their final rank (from Step 1). The sites were then grouped by transect and organized according to the total metals, water available metals and distance from the smelter. Other factors identified from the evaluation of the soil physical and chemical characterization LOE were also tabulated and compared.

The three-step procedure is illustrated in Figure 3-3.

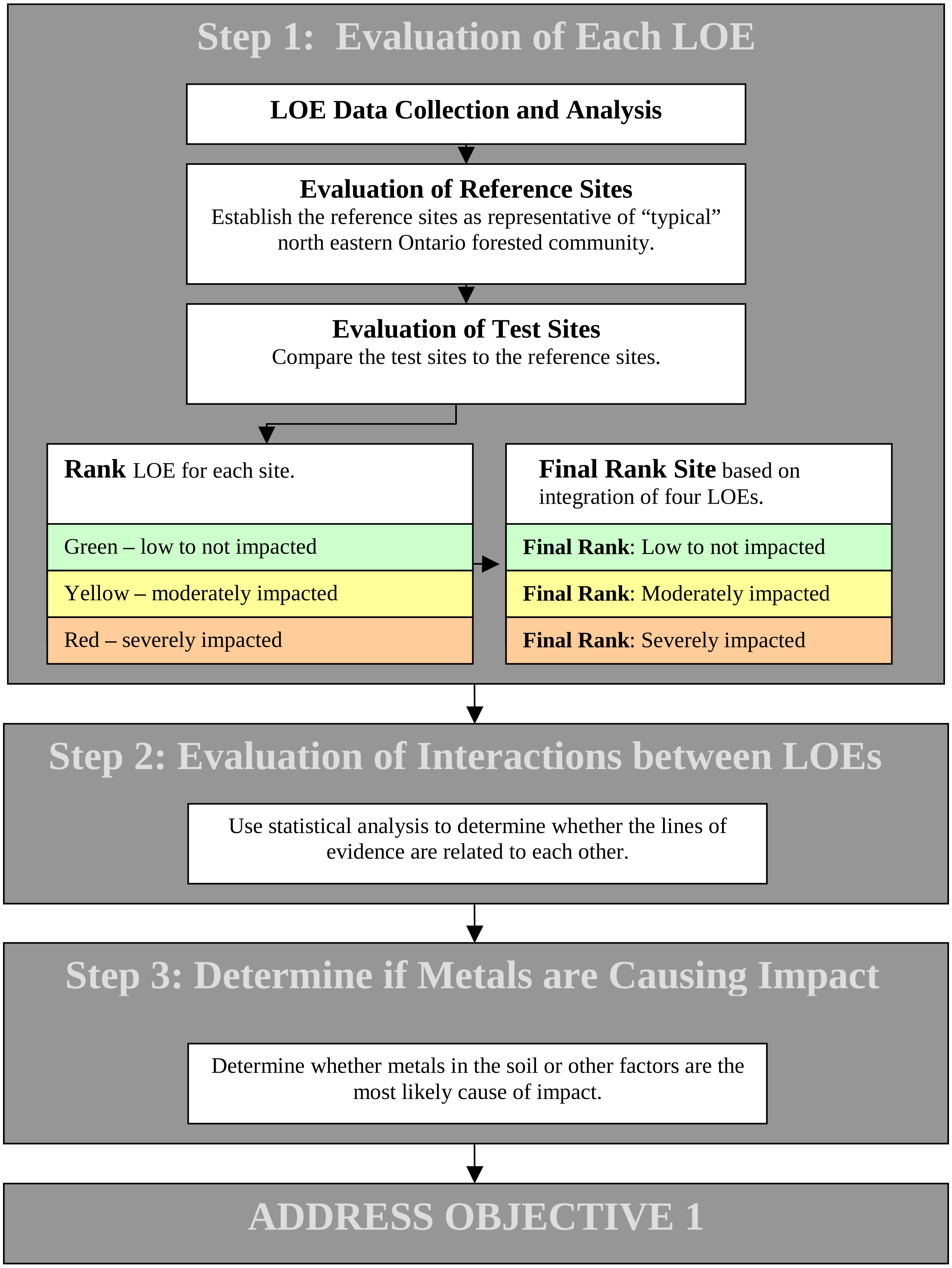

Figure 3-3 Overall Approach Used to Evaluate Objective #1

3.2.5 Site Selection Approach

A total of 22 study sites (18 test sites, one historically limed site and three reference sites) were selected within the Sudbury area. The term "test" site is used in the context of this study to refer to an exposure study site with soil metal levels or other conditions not considered indicative of Sudbury background conditions. The approaches used for site selection and site reconnaissance are outlined in the following sections.

Sampling sites were selected along three transects (Figure 3-4), radiating away from each smelter (Copper Cliff, Coniston and Falconbridge). The sites on each transect were selected on the basis of the following:

- Metal concentration (total copper and nickel);
- Soil pH; and
- Soil type.

Due to the re-greening initiatives, large areas of Sudbury have been treated with lime to increase soil pH. Many of these areas have also been seeded or planted to promote re-vegetation. Efforts were made during the site selection to avoid these areas and most sites were selected to have a soil pH indicative of a natural or unlimed situation. The test and reference sites for this study were selected to ensure a pH range of between 4.0 and 5.0 in the 0-5 cm surface soil depth to minimize the potential impact of pH variability in the various test results. However, for comparison purposes, one historically limed site adjacent to an unlimed area was included. Three reference sites were also selected. These were associated by soil texture and pH to at least one of the transects, and contained background concentrations of metals.

A variety of resources were used during the site selection process to determine the optimal areas for site placement, including the combined database of results from the 2001 Sudbury Soils Study; liming information provided by the City of Greater Sudbury; topographical maps and aerial photographs. Logistical issues were also considered during site selection including other development activities in the surrounding area, and accessibility. A detailed description of the site selection procedure is provided in Appendix GB Protocol No. 1. It should be noted that ecological criteria were not considered until the sites were already selected and, therefore, did not factor into the initial site selection.

3.2.6 Site Reconnaissance

Once the general area for the placement of a site was established, site reconnaissance was undertaken to complete the initial site characterization, which included the following activities:

- The centre of the site was staked and GPS points were recorded;
- Photographs of the site and surrounding area were taken from cardinal directions;
- A description of the site, including initial comments on soil type, a diagram of the site indicating sampling area boundaries, vegetation communities present, anecdotal information regarding site history, contour of the land, tree cover and proximity to roads or rail beds was recorded; and
- Soil core samples were collected (composite 0-5 cm sample consisting of >50 cores), which were submitted for analysis of total metal and pH at Testmark Laboratory, Sudbury. These results were used as the final determinant of the inclusion of a site into the study.

A detailed description of the site reconnaissance procedure is provided in Appendix GB Protocol No. 2. Directional pictures of the site are available in Appendix GC.

3.2.7 Site Locations

The sites were located on three transects radiating from the Copper Cliff, Coniston and Falconbridge smelters:

- Copper Cliff transect: seven test sites
- Falconbridge transect: five test sites
- Coniston transect: six test sites and one historically limed and re-greened site
- Reference: three reference sites

The sites were labelled according to the order in which they were located, and by the transect with which they were associated, as described in Appendix GB Protocol No. 3. The following codes were used to label the sites:

- Copper Cliff: CC
- Falconbridge: FB
- Coniston: CON
- Reference: REF

Three reference sites (REF-02, REF-03 and REF-04) were established with comparable pH and background soil metal concentrations. Once site identification was allocated it was not transferred to another site even if that site was excluded because it failed to meet the stipulated criteria. As a result the numeric continuity of the site numbering is sometimes interrupted (for example there is no REF-01 as this site was rejected because the soil textural analysis and pH indicated it was not a useful reference site).

The prevailing wind direction in Sudbury is predominantly from a southwest direction (Appendix GB-12 contains historic wind activity data for the Sudbury Area). The study sites generally corresponded to the location of the three smelters and the prevailing wind patterns (south west to north east). Conversely, the Copper Cliff transect was established against the general prevailing wind pattern as the City of Greater Sudbury was located in the intended direction. A map of the final location of the sites is shown in Figure 3-4. The term "transect" is used loosely to describe the orientation of the study sites. However, the sites are not oriented along a straight line or "transect" as logistical constraints such as site access or lack of soil strongly influenced actual site selection. The primary goal was to obtain a series of sites associated with each smelter that provided sufficient soil to study and provided a gradient of metal concentrations related to distances from each smelter.

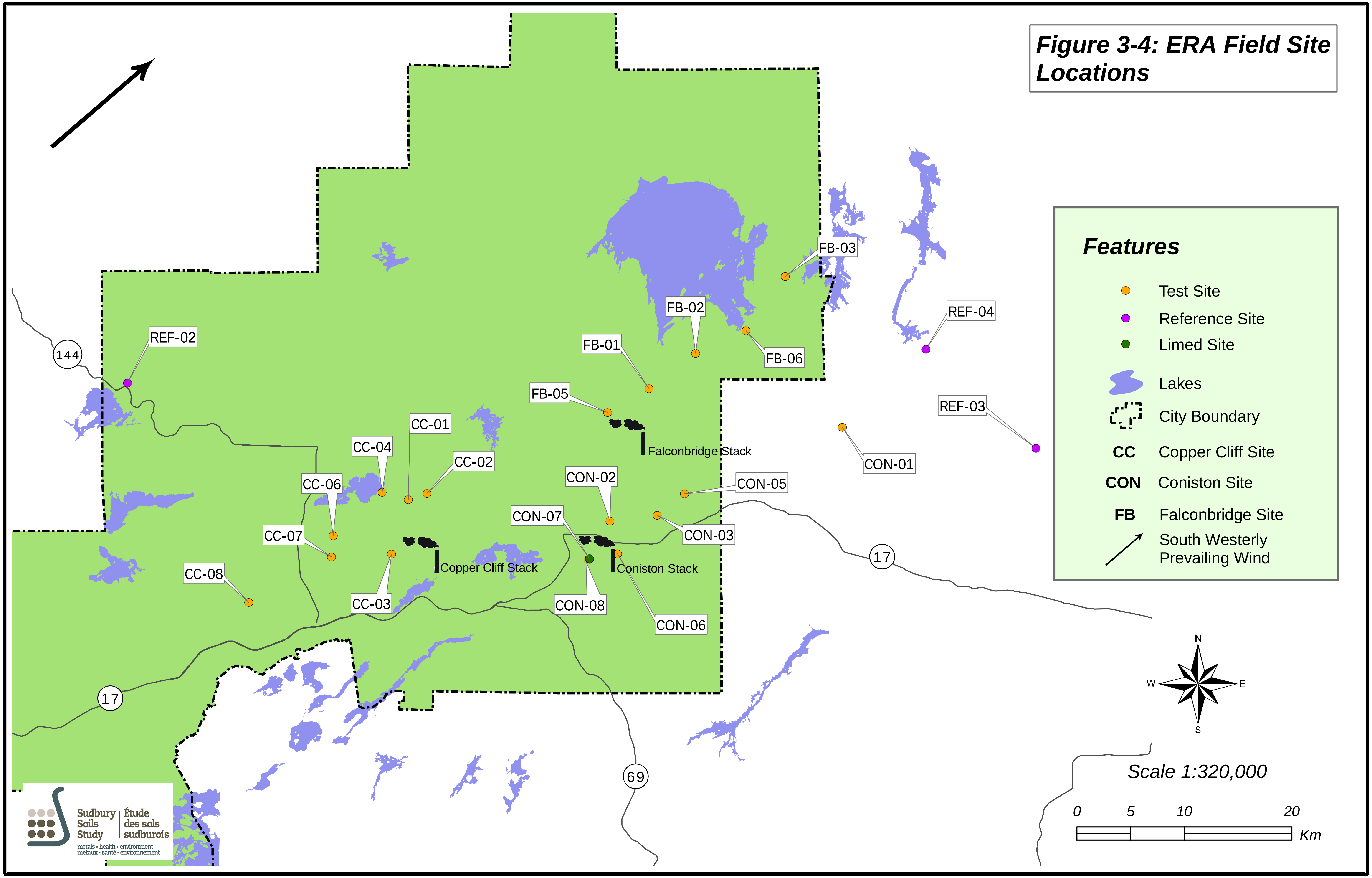

Figure 3-4: ERA Field Site Locations

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3.3 Soil Collection and Analysis: Methods and Results

The primary focus of the Sudbury Soils Study is the concentrations of COC in soil, which are metals (Cd, Cu, Co, Ni and Pb) and metalloids (As and Se). However, soil is a complex matrix of organic and inorganic constituents. In addition, the physical attributes of the soil, such as particle size, texture, and proportion of constituents (sand, silt and clay) all interact to define the quality of soil as a growth medium. The soil at each site was collected for physical characterization, chemical analysis and toxicity testing. The soil physical and chemical data were used in the first LOE presented in Section 3.4. The collection, analytical methods and results are described and presented in this section.

3.3.1 Soil Sample Collection

Soil was collected at each site for analytical determination and for use in toxicity testing. The soil samples collected for the majority of the physical and chemical characterizations are referred to as "soil core samples" and the bulk soil used for toxicity testing is referred to as "homogenized soil." In addition, bulk density samples and test pits were used to determine other physical properties. These samples were collected and handled in very different ways, denoting the different final uses of the samples. Guidance provided by Environment Canada (2005) on soil sample collection does not specify that a particular sample type (i.e., core or bulk) is required for specific analyses. Instead, Environment Canada (2005) states that "procedures used for sample collection (i.e., core, grab, or composite) will depend on the study objectives and nature of the [soil] being collected;" therefore, practical considerations determined the types of samples taken. Soil cores were taken for analysis of total and water extractable metals and pH for comparison with regional and other existing data, and according to MOE guidance. For toxicity testing, and other tests requiring large soil volumes, homogenized bulk samples were taken. (A comparison of total metal concentrations between the core and homogenized soil samples is presented in Section 3.16.4.)

3.3.1.1 Soil Core Collection

During the site reconnaissance, composite soil samples (Figures 3-5 and 3-6) consisting of >50 cores were collected from three depths: 0-5, 5-10 and 10-20 cm (or to refusal). The method used to collect the samples is detailed in Appendix GB Protocol No. 2. The collection dates for the core samples can be found in Appendix GD-1. The 0-5 cm soil core samples were submitted to the laboratory for analysis of total metals and pH. The results of this analysis confirmed whether a site was included in the study. A site was included if the soil pH was within the range of 4 to 5 and if the total Ni and Cu concentrations were within the established concentration gradient. Based on these conditions, once a site was included, the remainder of the chemical analysis were performed on the soil cores.

Figure 3-5 Field Collection of Soil Cores by SARA Personnel

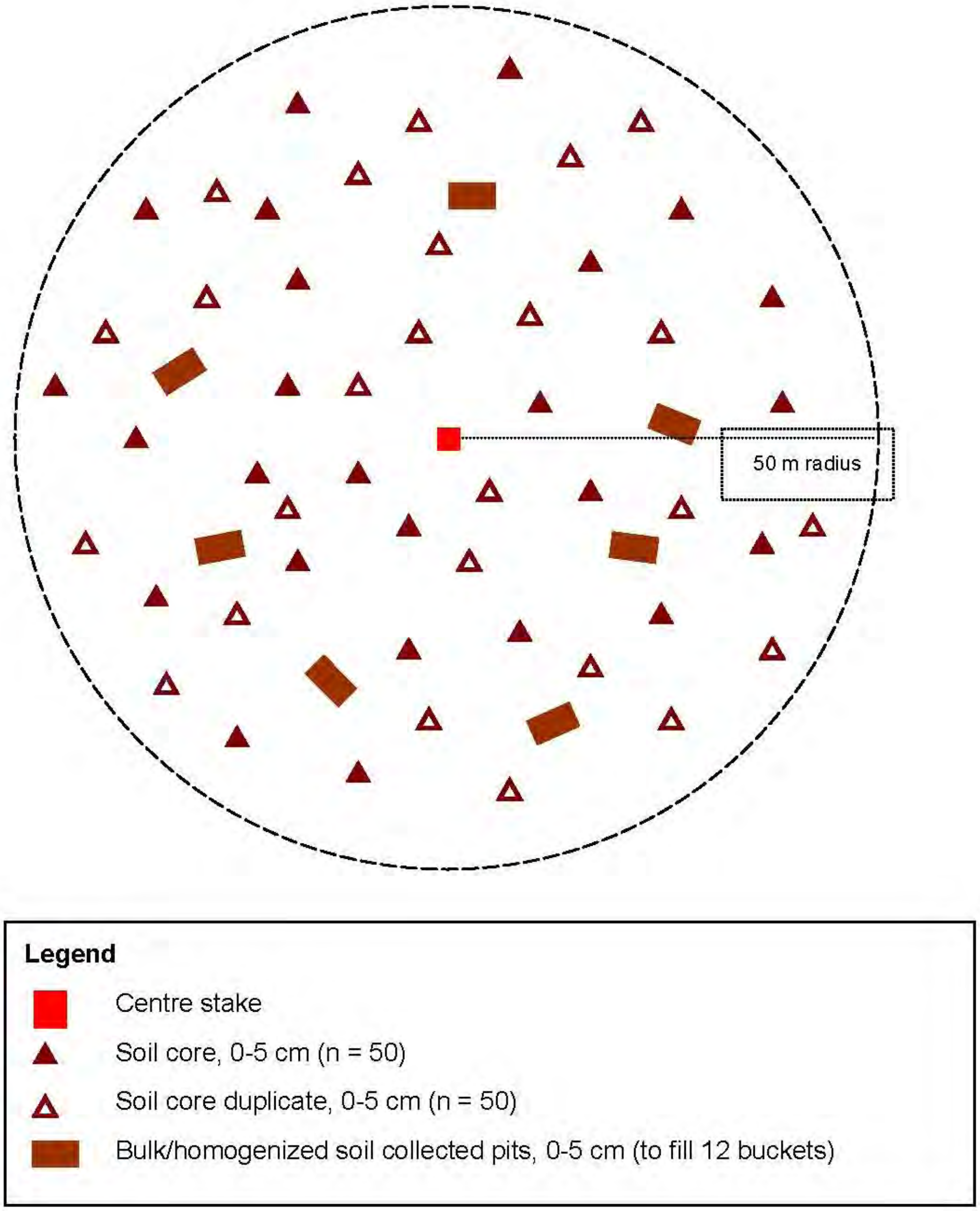


Figure 3-6 Schematic of Soil Core and Bulk Homogenized Soil Collection at Study Sites

3.3.1.2 Bulk/Homogenized Soil Collection

Following the completion of the plant community assessment at each site (presented in Section 3.5 and 3.6), a large quantity of soil was collected and homogenized for use in the toxicity testing (Figure 3-7). Further chemical testing was performed on the homogenized soil to complete the physical and chemical characterization of the site soil. The bulk homogenized soil consisted of a well-mixed sample of the 0-5 cm site soil collected from a variety of shallow test pits within 50 meters of the staked area. Efforts were made to collect samples that were representative of undisturbed soil layers not influenced by flooding or wind movement. The 0-5 cm layer was removed, sieved and homogenized. Before the buckets were sealed, one representative sample was collected by combining an equal amount of soil from each of the buckets to obtain a mass of 400 g. This sample was submitted for total metal and pH analysis to compare the characteristics of the homogenized soil to those of the core samples previously collected at the site. The details of the collection, sieving and homogenization of the soil are provided in Appendix GB Protocol No. 4. The protocol is consistent with the general sample collection guidance provided by Environment Canada in their Biological Test Method: Test for Measuring Emergence and Growth of Terrestrial Plants Exposed to Contaminants in Soil (Environment Canada, 2005). Appendix GD1 contains homogenized soil sample collection dates and the number of sieved buckets obtained from each site.

Figure 3-7 Preparation of Homogenized Soil Samples: a) & b) Sieving Bulk Samples; c) Mixing to obtain a Homogenized Sample; and, d) Collecting a Representative 400 g Sample and Packing Homogenized Soil Samples.

3.3.2 Analytical Methods

The site soil was analyzed for a variety of physical and chemical parameters. The rationale for the parameters chosen and methods used are briefly outlined in the following sections.

3.3.2.1 Physical Analysis

Physical aspects of the soil were determined both in situ and in collected samples. Table 3.2 summarizes the physical characteristics that were measured.

Table 3.2 Summary of Physical Characteristics Determined both *in situ* and in Collected Samples for Sudbury Test Site Soils

Parameter	Units	Soil Sample Analyzed	Facility	Method	Location of Results in ERA Report
Pedon Classification	-	*In situ* test pits	MIR	Visual classification of test pits.	Appendix GD5-1
Particle size distribution	% wt	0–5 cm core	SNL	Sheldrake and Wang in M.R. Carter Ed, 1993. Pipette method. Includes % sand, % silt, %clay, and textural classification.	Appendix GD5-2
Bulk density	g/cm^3	Undisturbed bulk density core	SARA	Parent and Caron, in M.R. Carter Ed, 1993	Appendix GD5-3

MIR = MIRARCO, Laurentian University
SARA – SARA Group
SNL = Soil and Nutrient Laboratory, University of Guelph

Pedon Classification

The characterization of the pedon layers at each site provided a description of the size of the ‘O’ horizon, which consists of the litter (L), fermentation (F) and humic (H) portions, and the ‘A’ horizon, which is characterized by having a large amount of organic material. The size of each of these horizons gave an indication of how well plants might grow in the soil and how mobile chemicals and nutrients might be.

Particle Size

Particle size distribution analysis was completed on the 0-5 cm core samples at the Soil and Nutrient Laboratory in Guelph. The particle size analysis provides a breakdown of the proportion of sand, silt and clay as defined by the textural classification of the soil. Soil texture affects a whole range of physical and chemical properties of the site soil and has important implications for soil fertility and the binding of metals.

Bulk Density

Bulk density samples were collected at all sampling sites to aid in determining soil structure, total pore space and the degree of packing of the soil particles. Moisture content of the soil was also determined from this sample. The details of the analysis of bulk density samples are presented in Appendix GB Protocol No. 7.

3.3.2.2 Chemical Analysis

The majority of the chemical analyses were conducted using the soil core samples, although additional analysis was also conducted in the homogenized soil for comparative purposes.

The following section describes treatment of the samples, the parameters measured and the methods used.

Sample Preparation

Soil Cores

The soil samples were prepared at Testmark Laboratories, Sudbury, with the exception of the fertility analysis conducted during the toxicity testing, which was performed at the Soil and Nutrient Laboratory (SNL) at the University of Guelph. A detailed description of the analytical methods used is provided in Appendix GB, Protocol 5, and in the Testmark internal document “Methodology for the Characterization of Soil Samples,” provided in Appendix GD-2.

Prior to analysis, the soil was thoroughly mixed, sieved and homogenized. The samples were then dried, ground and split into six portions. The preparation and analysis conducted on each of the portions of the core samples is shown in Figure 3-8.

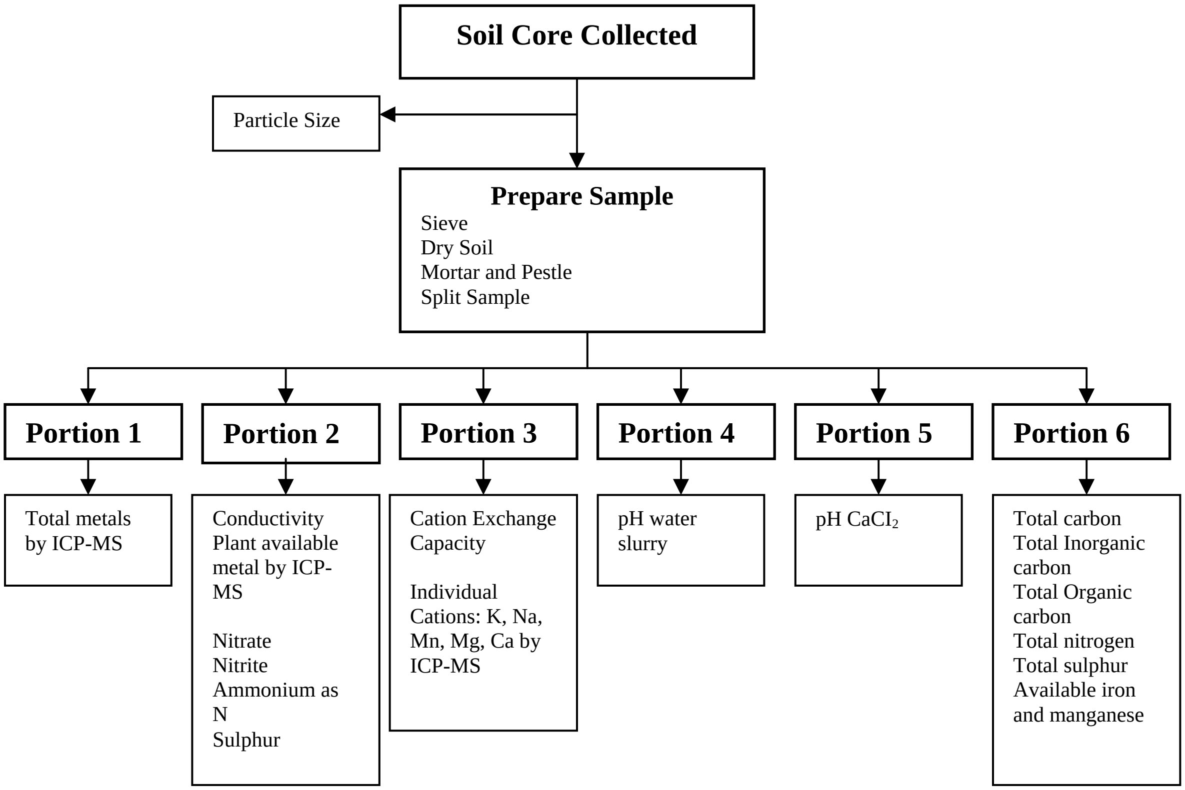


Figure 3-8 Summary of Analysis Conducted on Soil Cores from Sudbury Test Sites

Homogenized Soil

The preparation and analysis conducted on the homogenized bulk soil samples for toxicity testing is shown in Figure 3-9. Toxicity testing was conducted both in natural soils and in pH-amended (raised to a pH of 5.2) soils. Only the results in the natural soil were considered in the overall ranking of the toxicity testing LOE. The purpose of testing pH-amended soils was to determine whether altering pH would change toxicity of the soil. The pH was amended (raised) through the addition of calcium carbonate and the tests were run concurrently with natural site soils (Appendix GF-10).

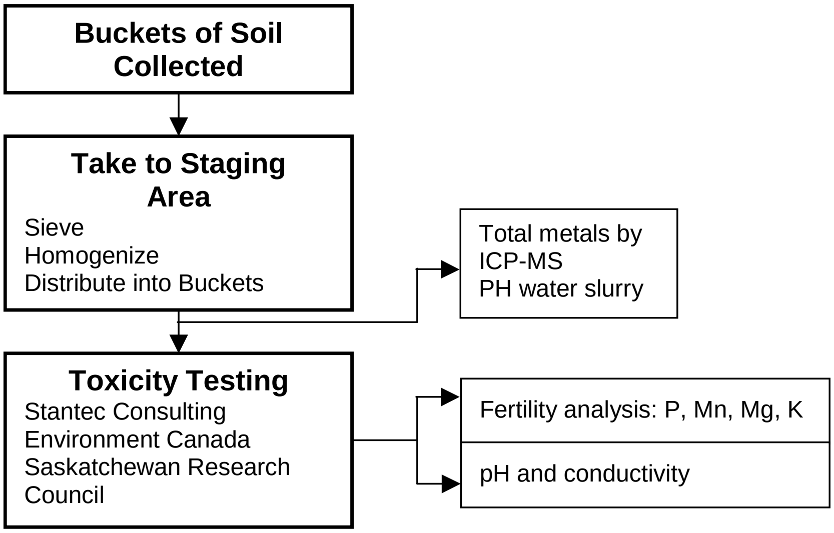


Figure 3-9 Summary of Analysis Conducted on Bulk Homogenized Soil from Sudbury Test Sites

Parameters Measured

A summary of the chemical parameters measured at each site, the units of measurement, the facility where the analysis was undertaken and the method used are provided in Table 3.3. The methods and a brief rationale for the measurement are provided in the following sections.

Table 3.3 Summary of Chemical Parameters Analyzed, Facility of Analysis, Method of Analysis, and Location of Results for Parameters Pertaining to Objective#1

Category	Parameter	Units	Soil Sample Analyzed	Facility	Method	Location of Results
Metals	Total Metals (HNO_3)	mg/kg	0–5 cm and Homogenized	TM	Microwave Digest by: Method 3051 ICP-MS by: SW846, Method 6020	Appendix GD6-1 (0-5 cm) Appendix GD7-1 (Homogenized Soil)
	Water Leach (plant available metals)	mg/kg[a] and µg/L	0–5 cm	TM	Water Leach extraction 1:5 sample:water ratio Analysis by ICP-MS by: SW846, Method 6020,	Appendix GD6-2 (0-5 cm)
pH and conductivity	pH in water	pH units	0–5 cm and Homogenized	TM	Modified APHA-4500	Appendix GD6-4
	Soil pH in 0.01 M $CaCl_2$	pH units	0–5 cm and Homogenized		Carter 16.3 M.R. Carter, Ed.,	
	Electrical Conductivity	uS/cm	0–5 cm		Modified APHA-2510.	
Organic Matter	Total, Organic and Inorganic	% dry	0–5 cm	SNL	ASTM E1915-01	Appendix GD6-5
	Total Nitrogen					
	Total Sulphur					
Soil Exchange Complex Chemistry	Cation Exchange	cmol(+)/kg	0–5 cm	TM	Carter 19.4 M.R. Carter, Ed.,	Appendix GD6-3
	Potassium	cmol(+)/kg	0–5 cm	TM	Ion Chromatography Modified SW846-9056.	Appendix GD6-3
	Sodium					
	Calcium					
	Magnesium					
	Manganese					
Fertility Analysis	Nitrogen: Nitrate, Nitrite and Ammonium as N	mg/L and mg/kg	0–5 cm	TM	Nitrate/Nitrite: Ion Chromatography Modified SW846-9056 Ammonium as N: Flow Analysis Modified APHA-4500.	Appendix GD6-6

Table 3.3 Summary of Chemical Parameters Analyzed, Facility of Analysis, Method of Analysis, and Location of Results for Parameters Pertaining to Objective#1

Category	Parameter	Units	Soil Sample Analyzed	Facility	Method	Location of Results
	Calcium, Phosphorous, and Sulphur	mg/L, µg/L and mg/kg	0–5 cm	TM	Water Leach extraction 1:5 sample:water ratio Analysis by ICP-MS by: SW846, Method 6020	Appendix GD6-6
	Available Iron and Manganese	mg/L soil and mg/kg soil	0–5 cm	SNL	DPTA-Extractable Carter 11 M.R. Carter, Ed., 1993.	Appendix GD6-6
Fertility Analysis in Homogenized Soil	Phosphorous	% difference	Homogenized soil start and finish of toxicity test	SNL	Sodium bicarbonate extractable P	Appendix GD7-3
	Potassium	% difference		SNL	Ammonium acetate extractable	Appendix GD7-3
	Water Leach Magnesium	% difference		SNL	Ammonium acetate extractable	Appendix GD7-3
	Water Leach Manganese	% difference		SNL	Sodium bicarbonate extractable Mn	Appendix GD7-3

TM = Testmark Laboratories

SNL = Soil and Nutrient Laboratory, University of Guelph.

[a.] Results from the water leach extractions were converted from µg/L to mg/kg using the result from the leachate (µg/L) multiplied by the standard volume (L) and the result is divided by the soil weight corrected for moisture (g). Soil moisture content was assumed to be 26.8%, and the soil mass used was assumed to be 20 g.

Metals

Both total metal and water leach metal levels were measured in the 0-5 cm soil cores samples. Once the soil for the toxicity testing was collected, sieved and homogenized, a sub-sample was submitted for total metal analysis to confirm whether the total metal concentrations were similar between the 0-5 cm core samples and the homogenized soil.

For the total metal analysis, the samples were digested using concentrated nitric acid and microwave heating and then analyzed by ICP-MS. The nitric acid extraction (total metals) was included to allow comparison to MOE Guidance values and data from the 2001 Sudbury Soil Study, along with being the standard approach to determine metal concentrations in soil (Nolan et al. 2003).

Because soil properties strongly affect solubility and phytotoxicity, analyzing the total concentration provides only partial information regarding the bioavailability of the metal. As a result, the SARA Group also submitted the same 0-5 cm core samples for analysis of water extracted (plant available) metal concentrations. The analysis of the water extracted metal concentrations provides a measure of the "labile" metal pool within the soil sample. For this method, the soil was mixed with water at a ratio of one part soil to five parts water. The mixture was shaken vigorously and the supernatant analyzed for metal concentration by ICP-MS. A water extraction isolates the water-soluble and labile metals (or free ions), which are typically viewed as the readily bioavailable fraction (Courchesne et al. 2006). By comparison, a more conventional dilute acid extraction of HNO_3 or HCl, developed for agricultural circum-neutral soils (soil pH above 5), has the potential to dissolve the iron and aluminium oxides present in the soil to which the metal is bound, thereby releasing more metal into solution and causing an inflated representation of the phytoavailable metal concentrations. Bioavailability is a much-debated topic in science at the present time; the inclusion of this extraction was discussed extensively among members of the SARA Group. The rationale for choosing a water extraction compared to a weak acid or salt extraction was based partly on professional judgment and the supporting literature (Sanders 1982; Reddy et al. 1995; Sauve et al. 1997; Els Smit et al. 1998; Kuinto et al. 1999), where the consensus around the table (experts present were Dr. Graeme Spiers, Dr. Peter Beckett, Dr. Keith Winterhalder and Dr. Mark Charbonnneau) was that a water extract would best represent the fraction of metal that is immediately available to the plant or soil organism.

Only the nitric acid and water extractable soil metal concentrations were included in the final discussions and ranking of the test sites during the ERA. However, during the course of the project, independent of the SARA Group, four additional soil extractions were performed under the supervision of Dr. William Hendershot in the Department of Natural Resource Science at McGill University. Sub samples of the homogenized soil were given to Dr. Hendershot to isolate and analyze the potentially plant available fraction. Four extraction techniques were employed. A brief description of the procedures, results and discussion concerning these analyses are provided in Section 3.15. The rationale for the extraction techniques as well as a detailed description of the methods employed and the results are provided in Appendices GD-6 and GD-7.

pH and Conductivity

Soil pH was determined by two separate methods in all of the collected 0-5 cm core samples and the homogenized soil: pH of a water/soil slurry, and calcium chloride buffer pH. The pH measured in water is considered to be the most accurate measure of the pH found in the field (Hendershot et al. 1993). The use of $CaCl_2$ pH is common in agricultural situations and is preferable in soil correlation work because the measurement is less dependent on recent fertilizer or liming events. The $CaCl_2$ method lowers the soil pH by about 0.5 units compared to the water slurry method.

Soil Organic Matter

Organic materials exert a profound influence on every facet of the nature of soil (Troeh and Thompson, 2005). The chemical composition of humus can be considered from the point of view of its elemental constituents, which are primarily carbon, hydrogen, oxygen and nitrogen and to a lesser extent sulphur. To gain an estimate of the soil organic matter, total carbon, organic carbon, inorganic carbon, total sulphur and total nitrogen were measured in the 0-5 cm core samples. This analysis was performed at the Soil and Nutrient laboratory at the University of Guelph.

Soil Exchange Complex Chemistry

Soil possesses electrostatic charges that counter (exchangeable) ions and form the exchange complex. The cation-exchange capacity (CEC) is a measure of the amount of ions that can be absorbed, in an exchangeable fashion, on the negative charge sites of the soil (Bache, 1976). The higher the CEC of the soil, the more ability the soil has to hold onto plant available soil nutrients and thus not lose them through leaching (Schroth and Sinclair, 2003). The ability of a soil to adsorb cations has very important implications for soil fertility (Schroth and Sinclair, 2003) and to the ability of soil to sorb metals due to ion exchange ability (Lanno, 2003). In the 0-5 cm soil core, the CEC was measured by the ammonium acetate method and the exchangeable cations were determined using the method outlined in Table 3.3 above.

Fertility Analysis

Using the methods outlined in Table 3.3, all 13 of the essential macronutrients (nitrogen, phosphorus, potassium, calcium, magnesium and sulphur) and micronutrients (iron, copper, manganese, zinc, boron, chlorine and molybdenum) required for plants to complete their life cycle were analyzed in the 0-5 cm core samples. In addition, during the toxicity testing, fertility analysis (phosphorous, potassium, manganese and magnesium) was performed on the homogenized samples at the start and finish of the test.

3.3.3 Quality Assurance and Quality Control

The quality assurance and quality control (QA/QC) approach used is discussed in Appendix GB Protocol No. 10. The processing and splitting of all samples was conducted according to prearranged methods discussed with Testmark Laboratories. An overview of the QA/QC approach used by Testmark is provided in the internal Testmark document, "Methodology for the Characterization of Soil Samples," provided in Appendix GD-2. The results of the internal QA/QC by Testmark Laboratories can be found at the end of each report. All laboratories used for analysis are accredited by the Canadian Association of Environmental Analytical Laboratories (CAEAL) and by the Standards Council of Canada (SCC). The methodology used by the laboratory for the cleaning, preparation and analysis of the sample was established prior to sample delivery. QC samples included field duplicate soil cores and analysis of certified reference material (CRM). Comparisons were made to determine if the percent difference between parameters measured in two samples were 30% or less. If the percent difference was greater than 30%, the cause of the difference between the samples was investigated. The following QA comparisons were made:

- comparisons between measured concentrations of 42 elements in original and field duplicate soil cores;
- comparisons between bulk densities in original and field duplicate samples;
- comparisons between measured concentrations of 42 elements in original and extra soil samples (i.e., between samples collected from a given site on different days);
- comparisons between measured concentrations of 14 elements in certified/standard reference materials and the certified values; and
- comparisons between measured concentrations of 29 elements in homogenized soil and soil core samples.

Field Duplicates

At each site, a duplicate soil sample was collected in the identical manner to the original sample to ensure the site was adequately represented. The analysis of the duplicate samples provided a measure of the variability of the soil metal content and the physical and chemical characteristics of the soil to ensure that each site was adequately represented by the sampling method. Duplicate samples were submitted from at least 10% of sites (randomly chosen, n=3) for analysis at Testmark Laboratories, Sudbury. Metal contents in 14 pairs of original and field duplicate soil core samples were compared. For all but five elements (bismuth, cobalt, lithium, molybdenum and titanium), more than 70% of the sample pairs had percent differences in concentration of less than 30%. For titanium, only 43% of sample pairs had acceptable differences in concentration, while 64% of sample pairs for bismuth, cobalt, lithium and molybdenum were acceptable. This analysis showed that the level of variability within sites in measured soil metal content was acceptable.

Bulk Density

Bulk density measurements from duplicate (and in one case triplicate) samples from eight sites were compared. One third (33.3%) of the sample pairs had percent differences in bulk density greater than 30%. This analysis shows some variability, which is to be expected since soil density can change from area to area. No corrective action was taken.

Extra Soil Samples

Soil sample collection was undertaken using a phased approach, meaning that, for some preliminary sites, a minimal amount of soil was collected until the location was confirmed as a test site, then the site was revisited and additional samples (the extra soil samples) were collected to make up the required mass. Prior to using the extra samples for additional analyses, comparisons were made between the original and extra samples to check that this would be appropriate. Metal contents in six pairs of original and extra soil core samples were compared. For nearly half the elements (20 out of 42), nearly 70% of the sample pairs had percent differences in concentration less than 30%. For the remaining 22 elements, as few as 17% of sample pairs had acceptable differences in concentration. This degree of variability is expected and acceptable; the extra soil samples were subsequently used for some of the analyses for their respective sites.

Certified Reference Materials

The SARA Group purchased certified reference material (CRM) to determine the variability related to the performance of the determination of metals in the soil samples. The CRM was purchased from the National Institute of Standards and Technology and consisted of San Joaquin Soil (CRM 2709). CRM samples were submitted to the laboratory for analysis on four occasions to check the accuracy of the results given by the laboratory. The measured concentrations of 14 elements in each submission were compared to the certified values for the reference material. For all but four elements (barium, lead, strontium and vanadium), more than 70% of the submissions differed from the certified value by less than 30%. Similarly, the percent recovery for all but the same four elements was greater than 75%.

The measured concentrations of 42 elements were also compared between the four submissions of reference material to check the consistency of the results given by the laboratory. Six comparisons were made. For all but two elements (mercury and molybdenum), more than 70% of the submission pairs has percent differences in concentration less than 30%.

Homogenized and Soil Core Samples

Homogenized and soil core samples were taken from each site to meet different testing/analytical needs. Metal contents in each pair of homogenized and soil core samples were compared to determine if the homogenized samples were representative of the soil cores from the same site. For the majority of elements (26 out of 29), nearly 70% of the sample pairs has percent differences in concentration less than 30%. In most cases, metal concentrations in soil cores were higher than in homogenized samples. This analysis shows that the homogenized samples are not representative of the soil core samples; however, this large variability is expected due to a lack of homogeneity in the core samples.

3.3.4 Physical and Chemical Results

The results of the physical soil analysis are provided in Appendix GD-5. The chemical soil analysis for the 0-5 cm cores is provided in Appendix GD-6. The results of the chemical analysis conducted on the homogenized soil are contained in Appendix GD-7. Summaries of the results for all analyses performed are presented in the tables below.

Physical Parameters

Table 3.4 summarizes the results of the bulk density and soil texture analyses at the test and reference sites. Bulk density had a relatively narrow range at the reference sites (0.72 to 0.88 g/cm^3), where as at the test sites the values ranged from 0.43 to 1.45 g/cm^3. Higher bulk densities are likely an indication of the exposed B horizons (mineral soils) at the eroded sites. Lower bulk density reflects a more complete soil profile, signifying that the surface soil includes both organic and mineral soil material.

Table 3.4 Summary of Physical Characterization of Soils from Test and Reference Sites

Parameter	Range by Transect			Coniston Limed Site (CON-07)	Reference Sites
	Copper Cliff	Falconbridge	Coniston		
Bulk Density (g/cm^3)	0.69 – 1.31	0.44 – 1.22	0.43 – 1.45	1.33	0.72 – 0.88
Soil Texture (# sites)					
Loam	2	2			2
Loamy Coarse Sand	1				
Silt Loam	4	2	4	1	1
Fine Sandy Loam		1	1		
Silty Clay Loam			1		

Total Metals (HNO_3) - Core Samples

Total metal results are presented for core samples and homogenized bulk soil samples. A comparison of the results is provided later in this section. The results of total Cu and Ni concentrations for core and homogenized samples are provided in Figure 3-10.

The full results of the ICP-MS scan of total (HNO_3) extractable metals in the 0-5 cm core samples are provided in Appendix GD-6-1. Total metals results for the Coniston smelter-related sites are provided in Table 3-5. Although data for all COC are presented, Ni and Cu results are discussed in the text to exemplify the range of values found along each transect. The lowest Ni and Cu concentrations were observed along the Coniston transect. Total Ni levels ranged from 70-255 mg/kg, while total Cu ranged from 49-240 mg/kg. Interestingly, the maximum Ni and Cu levels for this transect were found at CON-07, which is the historically limed and re-greened site and is a test site located close to the smelter. This limed site (CON-07) was immediately adjacent to a non-limed site (CON-08) and was used as a comparison of vegetation and toxicity results relative to soil pH and metal bioavailability as discussed in detail in Section 3.14.2. Maximum levels of the other COC (As, Cd, Co, Pb) were not found at CON-07.

Table 3.5 Total (HNO_3 extracted) COC Concentrations (mg/kg) and pH from Soil Cores along the Coniston Transect

Site	pH ($CaCl_2$)	Arsenic	Cadmium	Cobalt	Copper	Lead	Nickel	Selenium
CON-01	3.44	9.5	0.28	5.51	76	28	77	0.85
CON-02	3.76	12.7	0.17	9.01	195	15.0	138	1.0
CON-03	3.61	28	0.24	11.5	191	35	112	0.92
CON-05	3.59	11.4	0.44	11.0	118	15.1	92.9	0.7
CON-06	4.03	2.1	0.12	9.4	48.7	4.6	70.2	0.3
CON-07[a]	6.45	7.2	0.15	10.2	240	11.0	255	1.1
CON-08	3.96	5.2	0.15	10.9	107	9.1	132	0.89

[a] CON-07 is the historically limed and re-greened site. The pH is consequently much higher than the other test sites. It is not considered in the final site rankings but is discussed in greater detail in Section 3.14.2.

Nickel concentrations along the Falconbridge transect ranged from 78-422 mg/kg (Table 3.6), while total copper levels ranged from 87-655 mg/kg. The maximum levels of Ni, Cu, As, and Se were found at site FB-01. The lowest total metal levels were present at FB-03, the test site furthest from the smelter.

Table 3.6 Total (HNO_3 extracted) COC Concentrations (mg/kg) and pH from Soil Cores along the Falconbridge Transect

Site	pH ($CaCl_2$)	Arsenic	Cadmium	Cobalt	Copper	Lead	Nickel	Selenium
FB-01	3.21	117	0.99	23.3	655	162	422	5.6
FB-02	4.05	45	1.17	48.4	320	83	325	3.4
FB-03	3.64	10.9	0.28	4.84	87	28	78	1.1
FB-05	3.86	41	0.26	10.3	215	33	140	1.2
FB-06	3.48	26	0.61	11.7	200	61	179	1.7

The highest Ni and Cu concentrations were observed along the Copper Cliff transect (Table 3.7), where they were found to be 1100 mg/kg for Ni, and 1000 mg/kg for Cu (CC-03). In comparison, total Ni concentrations at the reference sites ranged from 39 to 46 mg/kg, while total Cu levels ranged from 19 to 42 mg/kg (Table 3.8).

Table 3.7 Total (HNO_3 extracted) COC Concentrations and pH from Soil Cores along the Copper Cliff Transect (mg/kg)

Site	pH ($CaCl_2$)	Arsenic	Cadmium	Cobalt	Copper	Lead	Nickel	Selenium
CC-01	3.81	46	1.26	26.7	960	70	700	6.2
CC-02	3.95	44	0.67	35.8	611	53	511	4.7
CC-03	3.81	72	0.61	41.5	1000	99.5	1100	10.5
CC-04	3.81	29	0.93	21.8	441	49	386	2.7
CC-06	3.85	15.5	0.43	9.9	144	17.2	103	1.5
CC-07	3.61	26	0.52	14.0	303	38	200	2.4
CC-08	3.62	9.6	0.27	7.81	97	29	77.5	1.4

Table 3.8 Total (HNO_3 extracted) COC Concentrations (mg/kg) and pH from Soil Cores from the Reference Sites

Site	pH ($CaCl_2$)	Arsenic	Cadmium	Cobalt	Copper	Lead	Nickel	Selenium
REF-02	3.59	4.6	0.28	4.87	42	33	46	1.0
REF-03	4.14	2.66	0.23	11.5	18.7	14	40	0.48
REF-04	3.6	5.85	0.17	5.35	39.3	18.6	38.9	0.75

Total Metals (HNO_3) - Homogenized Soil Samples

Tables 3.9 to 3.12 provide the total HNO_3 extracted metal values for homogenized soil samples and their pH for each of the test and reference sites. The complete list of results from the HNO_3 extraction for homogenized soil samples can be found in Appendix GD7-1. Table 3.9 summarizes the total (HNO_3 extracted) COC concentrations measured in the homogenized soil along the Coniston transect. The maximum soil Ni concentration was 313 mg/kg, while the highest total Cu level was 170 mg/kg both being from the historically limed site (CON-07). For the Falconbridge transect (Table 3.10), the highest total Ni and Cu concentrations were 535 mg/kg and 909 mg/kg respectively (FB-01). The highest total Ni and Cu concentrations were observed along the Copper Cliff transect (Table 3.11), where they were 1,100 mg/kg for Ni, and 948 mg/kg for Cu (CC-03). In comparison, total Ni concentrations at the reference sites ranged from 28 to 38 mg/kg, while total Cu levels ranged from 19 to 41 mg/kg (Table 3.12).

Table 3.9 Total (HNO_3 extracted) COC Concentrations (mg/kg) and pH from Homogenized Soil along the Coniston Transect

Site	pH ($CaCl_2$)	Arsenic	Cadmium	Cobalt	Copper	Lead	Nickel	Selenium
CON-01	3.94	5.3	0.17	6.6	32.1	7.9	33.9	0.62
CON-02	NA	5.9	0.1	5.52	96	7.0	60.7	0.51
CON-03	3.60	8.2	0.1	5.5	77.5	11.0	47.1	0.48
CON-05	3.55	13.0	0.46	8.91	144	17.0	125	1.1
CON-06	4.09	2.8	0.11	8.3	74.5	4.5	81.8	0.53
CON-07[a]	6.75	5.7	0.2	18.0	170	9.3	313	0.87
CON-08	3.87	2.5	0.12	13.1	80.1	6.4	106	0.44

[a] CON-07 is the historically limed and re-greened site. The pH is consequently much higher than the other test sites. It is not considered in the final site rankings but is discussed in greater detail in Section 3.14.2.

Table 3.10 Total (HNO_3 extracted) COC Concentrations (mg/kg) and pH from Homogenized Soil along the Falconbridge Transect

Site	pH ($CaCl_2$)	Arsenic	Cadmium	Cobalt	Copper	Lead	Nickel	Selenium
FB-01	NA	183	1.1	27.7	909	226	535	8.2
FB-02	NA	31	<0.01	39.1	162	33	127	1.3
FB-03	3.47	9.5	0.2	3.82	67.5	18	49.4	0.99
FB-05	NA	18	0.18	4.8	100	16	70.9	0.64
FB-06	3.72	14	0.29	6.3	80.6	19	52.3	0.86

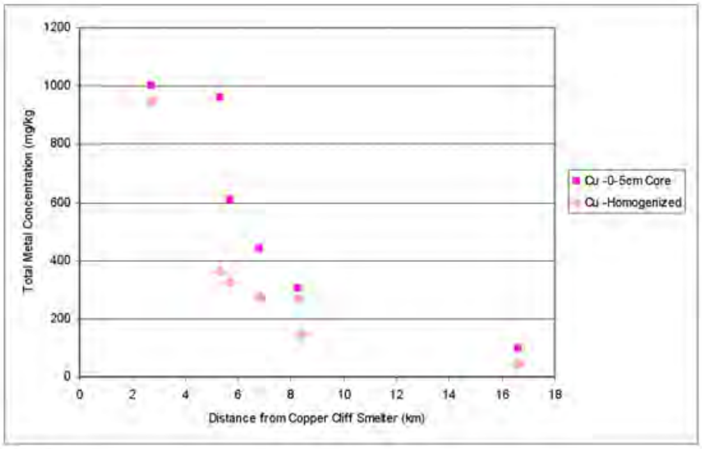
Table 3.11 Total (HNO_3 extracted) COC Concentrations (mg/kg) and pH from Homogenized Soil along the Copper Cliff Transect

Site	pH ($CaCl_2$)	Arsenic	Cadmium	Cobalt	Copper	Lead	Nickel	Selenium
CC-01	NA	28	<0.01	16.8	365	29	296	2.6
CC-02	NA	23	0.41	25.3	325	25	286	2.7
CC-03	NA	79	0.57	39.2	948	106	1100	9.6
CC-04	NA	20.9	0.41	11.8	273	26	255	2.2
CC-06	3.65	14.0	0.43	8.85	147	15.0	95	1.4
CC-07	NA	18.9	0.45	13.2	270	30.1	189	2.1
CC-08	3.84	3.6	0.12	4.14	41.2	9.3	27.2	0.51

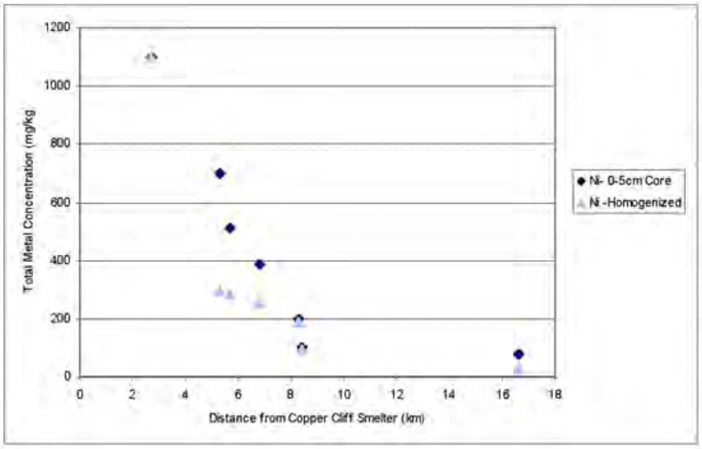
Table 3.12 Total (HNO_3 extracted) COC Concentrations (mg/kg) and pH from Homogenized Soil from the Reference Sites

Site	pH ($CaCl_2$)	Arsenic	Cadmium	Cobalt	Copper	Lead	Nickel	Selenium
REF-02	4.03	4.6	<0.01	3.95	40.7	26	31.9	0.92
REF-03	4.07	2.7	0.22	12.0	18.7	15	38.3	0.5
REF-04	3.57	6.3	0.18	4.47	38.4	21	27.6	0.64

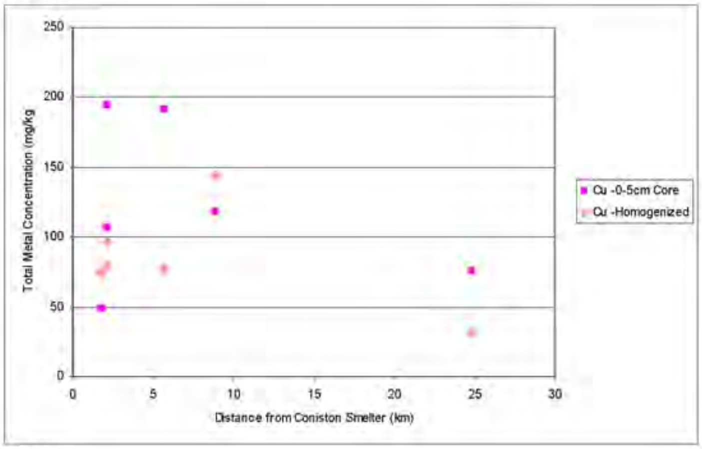
The general pattern of metal concentrations was similar between the core and bulk soil samples (Figure 3-10) but has absolute concentrations tended to be lower in bulk samples. This is discussed in more detail below (Table 3.17).



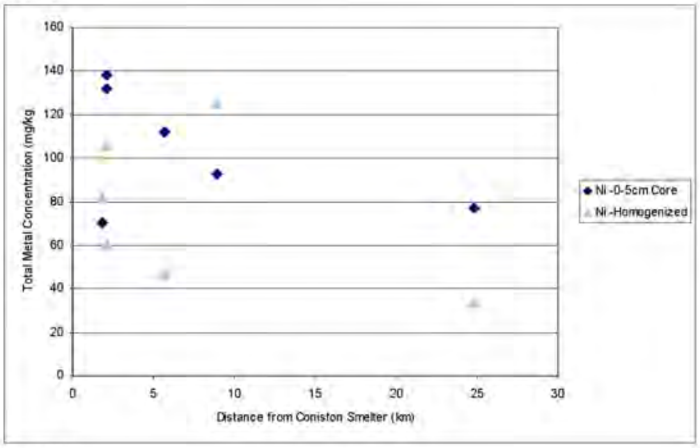
A) CC-Cu



CC-Ni



B) CON-Cu



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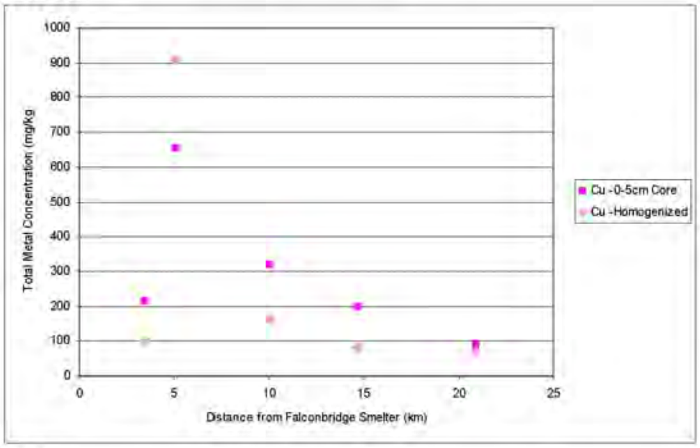
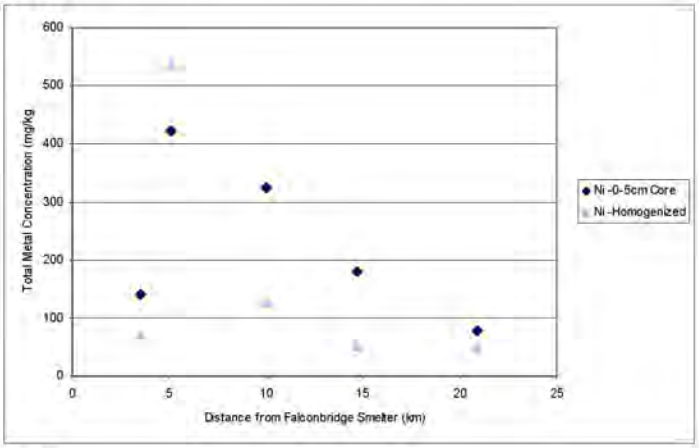


C) FB-Cu



FB-Ni

Figure 3-10 Total copper and nickel concentrations in soil on the a) Copper Cliff, b) Coniston and c) Falconbridge transects

Water Leach Metals - Core Samples

The following water leach results were converted from µg/L to mg/kg to allow for comparison with other extractions[1]. The conversions were made using the results from the leachate (µg/L) multiplied by the standard volume (L) and the result is divided by the soil weight corrected for moisture (g). Soil moisture content was assumed to be 26.8% and the soil mass used was assumed to be 20 g.

Tables 3.13 to 3.16 provide the COC concentrations from the water leach extraction and pH for the soil cores from each of the sites. The concentration of metal levels determined by water leach was up to 500 times lower than the total metal concentrations. Table 3.13 summarizes the water leach extracted concentrations of COC measured in the soil cores from the Coniston transect. The maximum soil Ni concentration was 2.55 mg/kg at CON-08, while the highest Cu level was 1.74 mg/kg at the historically limed site, CON-07. For the Falconbridge transect (Table 3.14), the highest Ni and Cu concentrations were 1.99 mg/kg and 1.47 mg/kg respectively (FB-01, FB-02). The highest Ni and Cu concentrations were observed along the Copper Cliff transect (Table 3.15), where they were 2.71 mg/kg for Ni, and 1.73 mg/kg for Cu (CC-02). In comparison, Ni concentrations at the reference sites ranged from 0.04 to 0.15 mg/kg, while Cu levels ranged from 0.01 to 0.08 mg/kg (Table 3.16).

Table 3.13 Water Leach COC Concentrations (mg/kg) and pH from Soil Cores along the Coniston Transect

Site	pH ($CaCl_2$)	Arsenic	Cadmium	Cobalt	Copper	Lead	Nickel	Selenium
CON-01	3.44	0.02	0.01	0.01	0.46	0.03	0.29	0.01
CON-02	3.76	<0.01	0.00	0.02	0.27	<0.01	0.40	<0.01
CON-03	3.61	0.03	0.00	0.01	0.44	<0.01	0.23	<0.01
CON-05	3.59	0.01	0.00	0.01	0.09	<0.01	0.38	<0.01
CON-06	4.03	<0.01	0.00	0.03	0.03	<0.01	0.98	<0.01
CON-07[a]	6.45	0.09	0.00	0.08	1.74	0.07	1.76	<0.01
CON-08	3.96	0.04	0.00	0.08	0.38	<0.01	2.55	<0.01

a CON-07 is the historically limed and re-greened site. The pH is consequently much higher than the other test sites. It is not considered in the final site rankings but is discussed in greater detail in Section 3.14.2.

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[1] The water leach results were used in their original, unconverted form for all statistical analyses. The converted data were used for soil characterization ranking. The data are presented in the Appendices in their converted form only.

Table 3.14 Water Leach COC Concentrations (mg/kg) and pH from Soil Cores along the Falconbridge Transect

Site	pH ($CaCl_2$)	Arsenic	Cadmium	Cobalt	Copper	Lead	Nickel	Selenium
FB-01	3.21	0.04	0.02	0.08	1.07	0.01	1.99	<0.01
FB-02	4.05	0.25	0.01	0.06	1.47	0.08	1.16	0.04
FB-03	3.64	0.01	0.00	0.02	0.08	<0.01	0.58	<0.01
FB-05	3.86	0.01	0.00	0.02	0.12	<0.01	0.31	0.01
FB-06	3.48	0.14	0.00	0.02	0.61	0.08	0.26	<0.01

Table 3.15 Water Leach COC Concentrations (mg/kg) and pH from Soil Cores along the Copper Cliff Transect

Site	pH ($CaCl_2$)	Arsenic	Cadmium	Cobalt	Copper	Lead	Nickel	Selenium
CC-01	3.81	0.03	0.01	0.04	0.52	<0.01	1.01	0.01
CC-02	3.95	<0.01	0.02	0.07	1.73	<0.01	2.71	<0.01
CC-03	3.81	<0.01	0.01	0.05	1.00	<0.01	1.56	0.02
CC-04	3.81	0.02	0.01	0.03	0.46	<0.01	1.67	0.01
CC-06	3.85	<0.01	0.00	0.02	0.17	<0.01	0.70	<0.01
CC-07	3.61	0.01	0.00	0.02	0.20	<0.01	0.45	<0.01
CC-08	3.62	<0.01	0.00	0.01	0.12	<0.01	0.24	<0.01

Table 3.16 Water Leach COC Concentrations (mg/kg) and pH from Soil Cores from the Reference Sites

Site	pH ($CaCl_2$)	Arsenic	Cadmium	Cobalt	Copper	Lead	Nickel	Selenium
REF-02	3.59	<0.01	0.00	0.01	0.03	<0.01	0.12	<0.01
REF-03	4.14	<0.01	0.00	0.00	0.01	<0.01	0.04	<0.01
REF-04	3.60	0.01	0.00	0.01	0.08	0.01	0.15	<0.01

pH and Conductivity

Table 3.17 summarizes the pH and conductivity measured at the test and reference sites. This analysis shows that all of the test site and reference sites have a pH (water/slurry), which is within the 4-5 range. The range of pH on all transects and at the reference sites was similar. The higher pH at the limed site (CON-07) reflects the liming activity that has occurred at this site.

Table 3.17 Summary of Soil pH and Conductivity Measured at Test and Reference Sites

Parameter	Range by Transect			Coniston Limed Site (CON-07)	Reference Sites
	Copper Cliff	Falconbridge	Coniston		
pH (water/slurry)	4.19 – 4.81	4.1 – 4.77	4.34 – 4.60	7.19	4.04 – 4.88
pH ($CaCl_2$)	3.61 – 3.95	3.21 – 4.05	3.44 – 4.03	6.45	3.59 – 4.14
Conductivity (µS/cm)	16 – 58.4	16.9 – 112.4	15.5 – 65.7	44.1	24.6 – 41.1

Soil Organic Matter

Table 3.18 summarizes the soil organic matter as measured by: total, organic and inorganic carbon; total nitrogen; and, total sulphur at the test, limed and reference sites.

Table 3.18 Summary of Total C, N and S Measured at Test and Reference Sites

Parameter	Range (% Dry) by Transect			Coniston Limed Site (CON-07)	Reference Sites
	Copper Cliff	Falconbridge	Coniston		
Total Nitrogen	0.13-0.3	0.1-0.35	0.03-0.27	0.09	0.23-0.34
Total Sulphur	<DL-0.13	<DL	<DL	<DL	<DL
Total Carbon	2.29 – 5.59	1.76 – 7.73	0.46 – 3.75	1.83	4.24 – 7
Organic Carbon	2.29 – 5.59	1.76 – 7.73	0.45 – 3.75	1.71	4.18 – 6.93
Inorganic Carbon	0 – 0.21	0 – 0.05	0 – 0.12	0.12	0 – 0.07

<DL indicates concentration was less than the method detection limit

Soil Exchange Complex Chemistry

Table 3.19 summarizes the cation exchange capacity and measurement of cations at the test, limed and reference sites.

Table 3.19 Summary of Cation Exchange Capacity and Quantification of Individual Cations in Test and Reference Site Soils

Parameter	Range by Transect (cmol+/kg)			Coniston Limed Site (CON-07)	Reference Sites
	Copper Cliff	Falconbridge	Coniston		
Cation Exchange Capacity	16.8 – 52.1	11 – 124	11 – 45.4	14.6	27.4 – 29.1
Potassium	0.12 – 0.28	0.12 – 0.57	0.11 – 0.38	0.16	0.15 – 0.24
Sodium	0.02 – 0.06	0.01 – 0.1	0.02 – 0.12	0.054	0.03 – 0.04
Calcium	0.15 – 2.1	0.24 – 3.83	0.11 – 1.8	9.4	0.38 – 2.8
Magnesium	0.05 – 0.3	0.05 – 0.81	0.05 – 1	1.3	0.18 – 0.72
Manganese	<DL – 0.2	<DL – 0.32	<DL – 0.21	<DL	<DL

<DL indicates concentration was less than the method detection limit

Fertility

The nutrient concentrations at the test and reference sites are summarized in Table 3.20.

Table 3.20 Summary of Soil Nutrient Concentrations at Test and Reference Sites (Soil Cores 0 – 5 cm)

Nutrient	Measurement	Unit	Range by Transect				
			Copper Cliff	Falconbridge	Coniston	Coniston Limed Site (CON-07)	Reference Sites
Nitrogen	Total N	% dry	0.13 – 0.3	0.1 – 0.35	0.04 – 0.27	0.09	0.23 – 0.34
	Nitrate	mg/kg	<DL – 22.5	<DL – 35.5	<DL – 3.28	<DL	<DL – 23.2
	Nitrite	mg/kg	<DL	<DL	<DL	<DL	<DL
	Ammonia	mg/L	0.01 – 11.5	0.2 – 36	0.01 – 3.2	0.10	0.45 – 3.5
Phosphorous	Total P	mg/kg	550 – 2500	240 – 700	180 – 850	180	208 – 501
	Water leach P	µg/L	<DL	<DL – 3.01	0.003 – 2.12	310	<DL – 0.17
Sulphur	Total S	% dry	<DL – 0.13	<DL	<DL	<DL	<DL – 0.03
	Water leach S	µg/L	<DL – 0.02	0.02 – 0.06	0.01 – 0.06	4100	<DL – 0.01

Table 3.20 Summary of Soil Nutrient Concentrations at Test and Reference Sites (Soil Cores 0 – 5 cm)

Nutrient	Measurement	Unit	Range by Transect				
			Copper Cliff	Falconbridge	Coniston	Coniston Limed Site (CON-07)	Reference Sites
Iron	Total Fe	mg/kg	861 – 1864	676 – 1876	222 – 2442	9300	919 – 1256
	Water leach Fe	µg/L	<DL – 1.23	0.32 – 22.5	<DL – 225	33 000	0.5 – 3.1
Manganese	Total Mn	mg/kg	19 – 205	4.8 – 266	12.3 – 109	130	38 – 103
	Water leach Mn	µg/L	0.29 – 3.5	0.38 – 4.2	0.07 – 1.5	190	0.31 – 0.72

<DL indicates concentration was less than the method detection limit

3.3.5 Representation of the Study Area

A considerable amount of effort was devoted to finding suitable test sites that contained a range of soil metal levels that were considered representative of the Sudbury area and had a pH that was between 4 and 5 (water slurry method). In the following section the metal levels and pH of the soil samples collected for the ERA are compared to the soil samples collected for the regional study in 2001 to determine whether they are representative of the Sudbury natural environment.

The results of the 2001 soils study clearly showed that metal levels were higher in soils from residential properties in urban areas compared with soils from more rural undisturbed areas. This is not surprising given that many of the urban areas are located much closer to the smelters than the rural, undisturbed natural sites. Therefore, it is appropriate to compare metal levels from our ecological test sites with the rural or regional survey results (CEM 2004) to determine if they reflect the range of conditions across the entire study area.

In 2001 Laurentian University researchers conducted the Sudbury regional survey (n=368) to determine the concentration of metals in the soil. This study aimed to collect soil samples in more remote and undisturbed areas to determine the spatial extent (geographic area) of the smelter "footprint". (For further information refer to Chapter 7 of Volume I). The COC concentrations at the 22 sites established during the Objective #1 studies were compared to those established during the remote survey in an effort to confirm that the levels of COC at the study sites were representative of the Sudbury region. The results of this comparison are shown in Figures 3-11 and 3-12 using Ni and Cu as examples.

Figures 3-11 and 3-12 represent box-whisker plots of the log concentration of Cu and Ni, respectively, for the regional 2001 soil survey (n=368) and for the 3 transects used in the ecological risk assessment (total n=22). There is a greater range of metal levels in the regional survey as would be expected with the much larger sample size. However, there is a good overlap of samples within the interquartile range (this is the area shown in the "boxes" and represents the 25th to the 75th percentile). Two outlier values are identified as open circles.

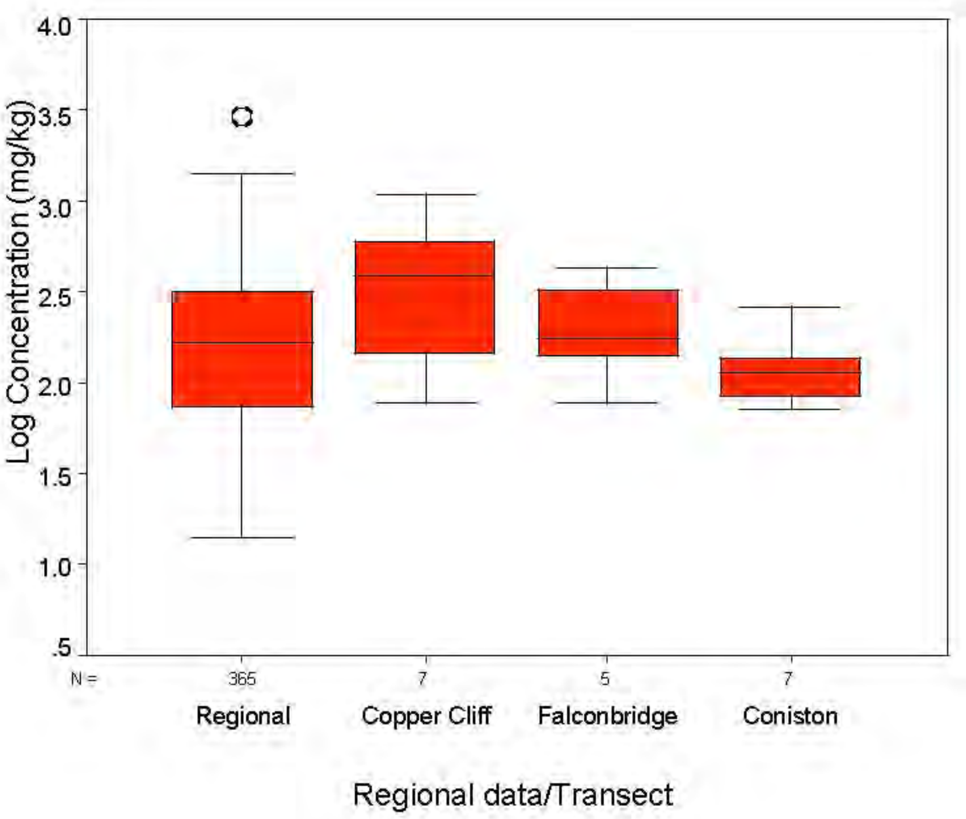


Figure 3-11 **Log Distribution of Copper Levels in Soil Cores (0-5 cm) in each Transect and the Regional Soil Survey**

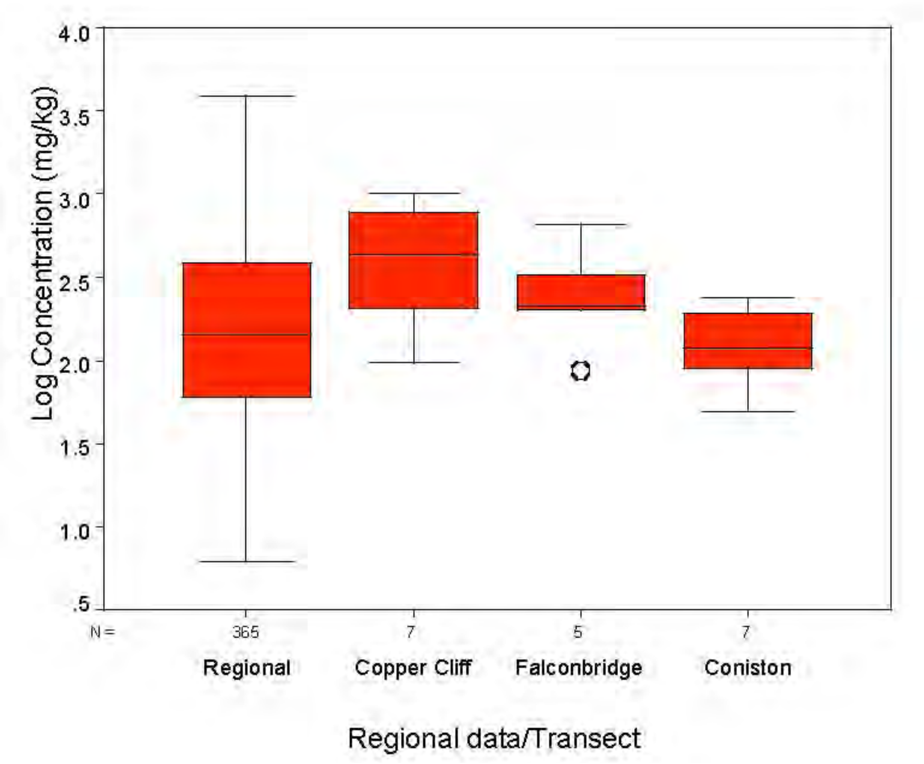


Figure 3-12 Log Distribution of Nickel Levels in Soil Cores (0-5 cm) in each Transect and the Regional Soil Survey

The data are compared in another fashion in Figures 3-13 and 3-14 for Ni and Cu, respectively. Theses Figures illustrate the frequency distribution of metal concentrations in the ERA sites (n = 22) and the regional survey sites. These Figures clearly show two trends, a) the data are skewed with more values at the lower concentrations, and b) metal levels in the ERA sample sites closely mirror the distribution of metal levels across the regional survey.

During the 2001 Sudbury regional survey, pH was determined using two methods (water slurry and $CaCl_2$). At all 368 sites data is available for the $CaCl_2$ pH levels, but only a partial dataset (112 sites) is available for the water slurry method. During the ERA, pH was determined using both methods, although site selection was based upon the water slurry method only. For the purposes of comparison, the results of both pH methods have been plotted. It is important to remember that the water slurry results for the regional data are based on a partial dataset (n = 112).

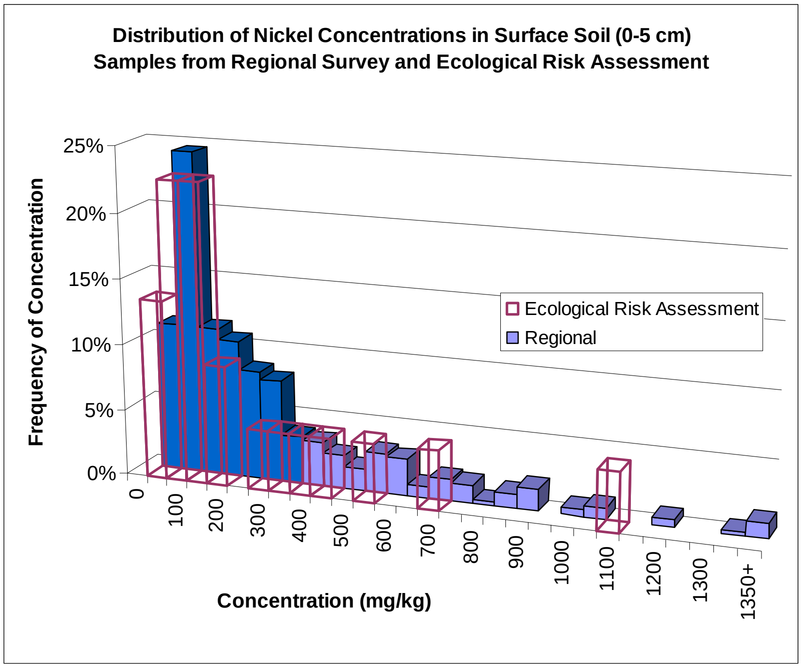


Figure 3-13 Comparison of the Distributions of Nickel Concentrations in Surface Soil (0-5 cm) Core Samples Collected for the Regional Soil Survey (n = 386) and the ERA Objective #1 Studies (n = 22)

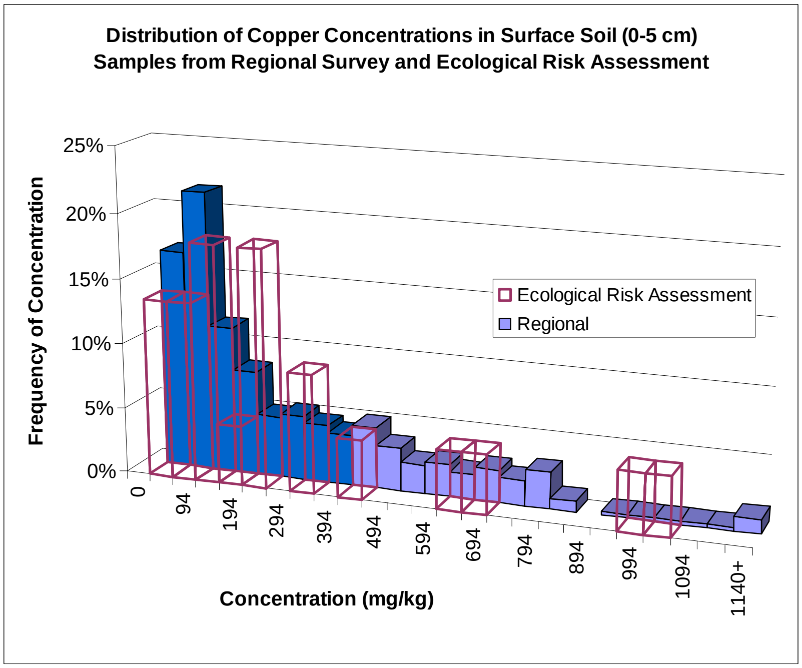


Figure 3-14 Comparison of the Distributions of Copper Concentrations in Surface Soil (0-5 cm) Core Samples Collected for the Regional Soil Survey (n = 386) and the ERA Objective #1 Studies (n = 22)

Figure 3-15 illustrates the frequency of distribution of the pH using the water slurry pH results for the ERA samples (n = 22) compared to the regional survey (n = 112). Figure 3-15 also shows that as per the study design the majority of samples collected for the ERA (95%) have a pH (water slurry) that is between the 4 and 5, the remaining 5% represents the limed site at CON-07. The majority of the samples collected during the regional survey in 2001 (70%) also have a pH that is within this range. Of the remaining samples 3% had a pH that was lower (ranging from pH 3.6 - 3.8) and 28% had a pH that was higher (ranging from 5.2 to 6.4). The samples for the 2001 regional survey represent the whole of the Sudbury region which includes the farming regions in the Bleazard Valley and some sites close to urban areas both of which would likely have a pH that is greater than 5.

Figure 3-16 illustrates the frequency of distribution of the pH using the $CaCl_2$ pH results for the ERA samples (n = 22) compared to the regional survey (n = 368) Figure 3-16 shows that the majority of samples collected for the ERA (95%) have a pH (water slurry) that is between 3.4 and 4.2, the remaining 5% represents the limed site at CON-07. The majority of the samples collected during the regional survey in 2001 (74%) also have a pH that is within this range. All of the remaining samples (26%) have a pH that was higher (ranging from 4.4 to 6.8).

The results shown in Figure 3-15 and 3-16 indicate that the pH range chosen for the ERA study sites is representative of the pH in natural areas in the Sudbury region.

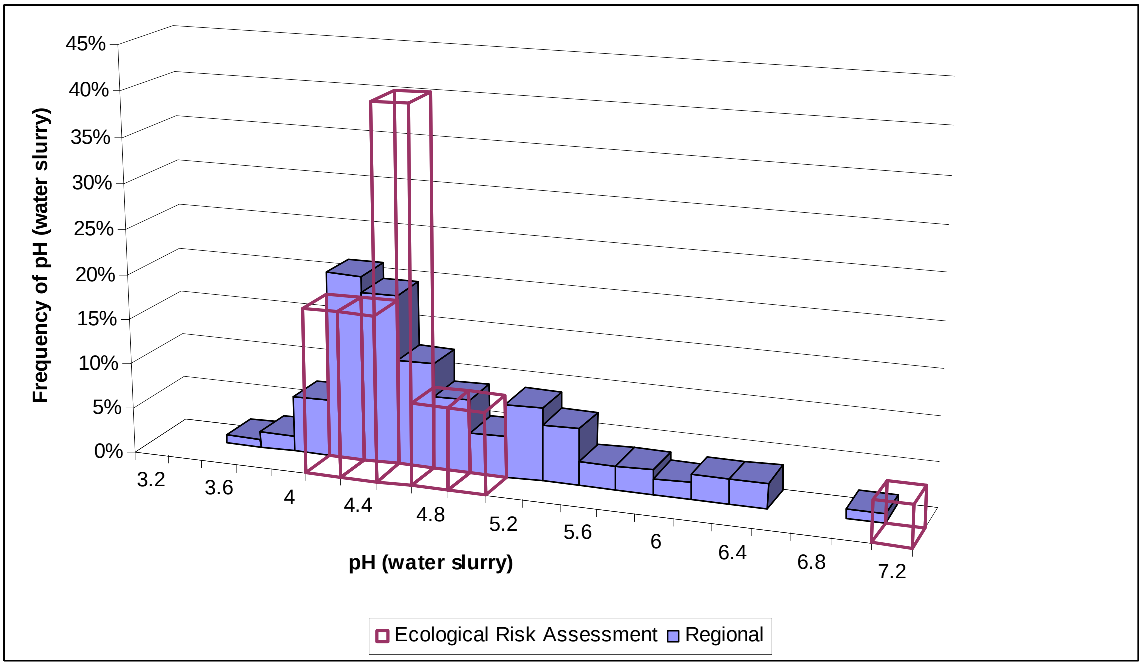


Figure 3-15 **Comparison of the Distributions of pH (water slurry) in Surface Soil (0-5 cm) Core Samples Collected for the Regional Soil Survey (n=112) and the ERA Objective #1 Studies (n=22)**

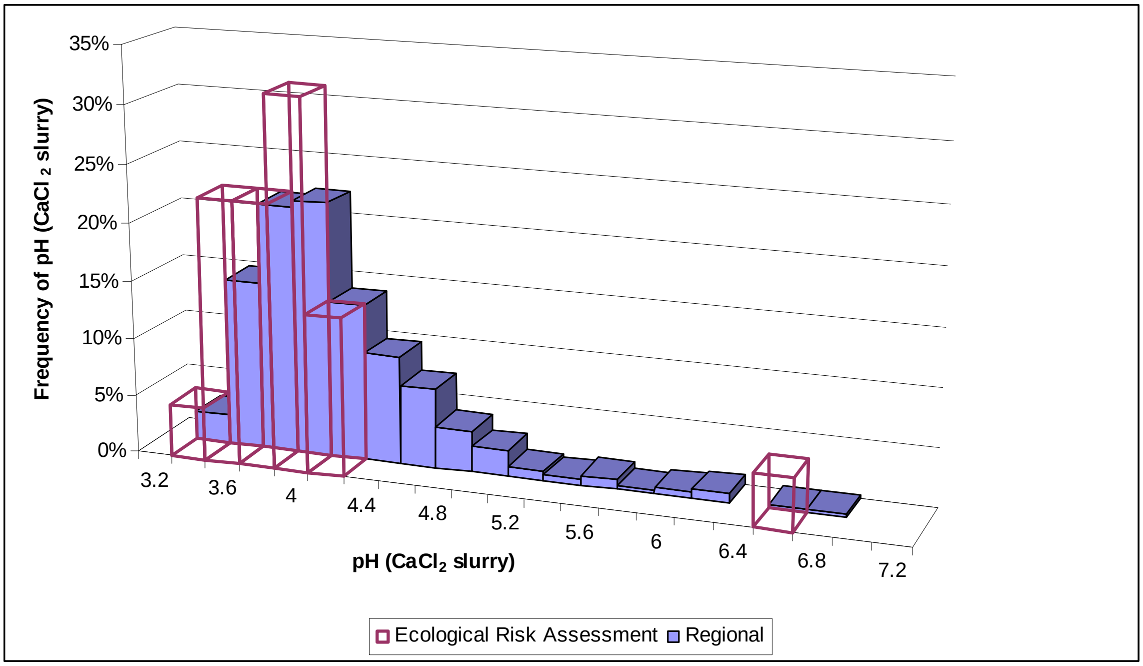


Figure 3-16 **Comparison of the Distributions of pH (calcium chloride slurry) in Surface Soil (0-5 cm) Core Samples Collected for the Regional Soil Survey (n=367) and the ERA Objective #1 Studies (n=22)**

In summary, the study team is very confident that the field sites chosen for the ERA are very representative of metal concentrations and pH present in the general Sudbury rural environment.

3.4 Soil Characterization LOE (Step 1)

The objective of this line of evidence was to describe in detail the soil physical and chemical parameters to determine whether the test site soils could be considered a suitable medium to support plant growth.

The primary focus of the Sudbury Soils Study is directed at the concentrations of COC in the soil. However, soil is a complex matrix of organic and inorganic constituents and these other factors may also influence plant growth. The physical attributes of the soil, such as particle size, texture, and proportion of constituents (sand, silt and clay), all interact to define the quality of the soil as a growth medium. These underlying characteristics have a profound effect on the types of plants and vegetation that can grow in a particular soil type. The ranking associated with this LOE focuses on a variety of physical and chemical soil characteristics measured to assess the soil as a growth medium. The ranking approach compares the test site soils to soil quality parameter ranges that were established using literature review values, reference site values and best professional judgment (described below). A final ranking for each test site was based on soil characteristics, not including the chemicals of concern (COC). The metal concentrations of the site soils were not considered during the ranking of this LOE but were considered during Step 2 and Step 3 of the overall process (see Section 3.3 and Figure 3-3 for more details). Many of the soil parameters examined have likely been altered over time by the smelter emissions and the smelting activities in the Sudbury region. This ranking approach acts as a “snapshot” of the soil conditions at the time of sampling and does not attempt to quantify the past influences on the site soils.

The methods used for soil collection and analysis and the subsequent results were presented earlier in Section 3.3. The ranking of the test sites based on physical and chemical characteristics is presented in detail in the “Soil Characterization LOE Ranking Report” located in Appendix GD-9. An overview of the approach and a summary of the resulting ranks are presented in the following sections.

3.4.1 Overview of the Ranking Approach

The approach used to rank the soil characterization results is summarized in Figure 3-17 and in the steps outlined in the following sections.

At each site, the following categories of soil quality parameters were assessed, and are summarized below (detailed descriptions can be found in Appendix GD-9):

- Parent Material
- Soil Development
- Organic Matter
- Soil Exchange Complex Chemistry
- Fertility

Parent Material

The texture of the parent material controls the internal drainage class of the soils developed on them, which range from well drained on the coarser textured soils to imperfectly drained on the finer textured glaciolacustrine sites. Although these parameters are important from the perspective of soil development, they were not utilized in the soil characterization LOE ranking as they were used in the ranking for the Plant Community Assessment LOE. The parent material was included and discussed as part of this assessment, but not used as a ranking criterion.

Soil Development

On many sites, the record of soil development has been affected by erosive events following the removal of stabilizing vegetation (Appendix GD5-1). The pedon descriptions reflect these erosive impacts by documenting the variety of incomplete horizon sequences. The loss of surface horizons by erosion implied a loss of organic matter, nutrients and stabilizing materials crucial for sustainable plant growth.

Organic Matter

The amount of organic matter in soil is a function of the addition of fresh material and the decomposition rate. Despite the fact that plants do not require organic matter as such for growth and development, it is still considered one of the most important components of soil fertility because of its influence on a wide range of soil properties and processes (Gregorich et al., 1994; Schroth, 2003.). The quality of soil organic matter at each site was ranked relative to baseline conditions documented in the reference sites. Key soil organic matter components evaluated include total carbon and nitrogen levels.

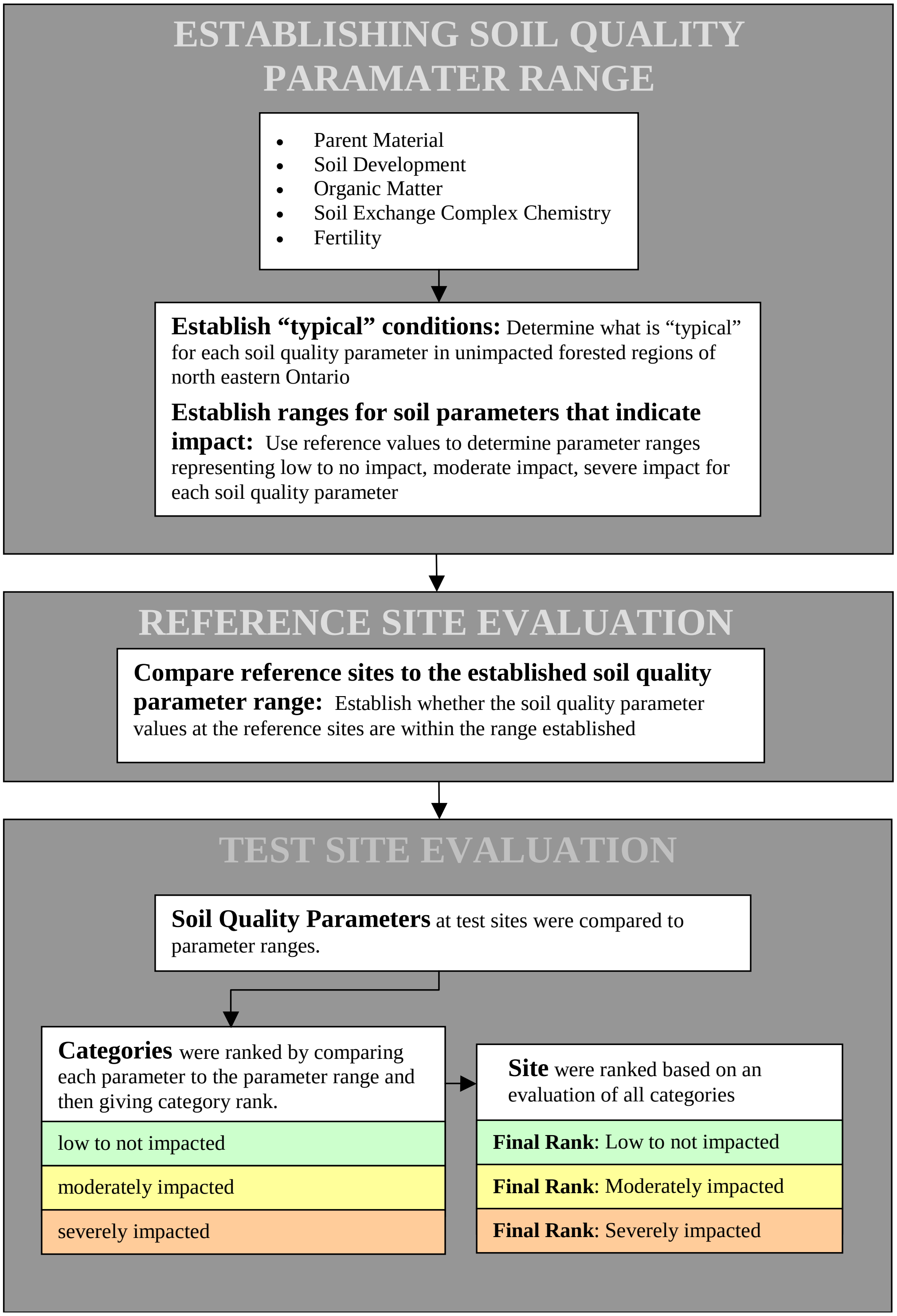
Soil Exchange Complex Chemistry

Soil quality parameters include the cation exchange capacity, the concentrations of Ca, Mg, the Ca:Mg ratio and base saturation. Of these parameters, cation exchange capacity was considered the strongest determinant of soil quality.

Fertility

The 13 nutrient elements plants require to complete their life cycle are referred to as essential plant nutrients. Each of these nutrients has a critical function and is required in varying amounts in plant tissue. Macronutrients (nitrogen, phosphorus, potassium, calcium, magnesium and sulphur) are required in the largest amount in plants. Micronutrients (iron, copper, manganese, zinc, boron, molybdenum and chlorine) are required in relatively smaller amounts.

The overall fertility of the sites was evaluated by examining the concentrations of the macronutrients: nitrogen, phosphorus, potassium and magnesium; and of the micronutrients: iron and manganese. The macronutrients were considered stronger determinants of soil quality than the micronutrients.



ESTABLISHING SOIL QUALITY PARAMATER RANGE

- Parent Material
- Soil Development
- Organic Matter
- Soil Exchange Complex Chemistry
- Fertility

Establish "typical" conditions: Determine what is "typical" for each soil quality parameter in unimpacted forested regions of north eastern Ontario

Establish ranges for soil parameters that indicate impact: Use reference values to determine parameter ranges representing low to no impact, moderate impact, severe impact for each soil quality parameter

REFERENCE SITE EVALUATION

Compare reference sites to the established soil quality parameter range: Establish whether the soil quality parameter values at the reference sites are within the range established

TEST SITE EVALUATION

Soil Quality Parameters at test sites were compared to parameter ranges.

Categories were ranked by comparing each parameter to the parameter range and then giving category rank.

- low to not impacted
- moderately impacted
- severely impacted

Site were ranked based on an evaluation of all categories

- **Final Rank**: Low to not impacted
- **Final Rank**: Moderately impacted
- **Final Rank**: Severely impacted

Figure 3-17 Final Ranking Scheme for Test and Reference Site Soils Based on Soil Chemistry Parameters

The following steps were taken to evaluate the reference sites and to define the soil quality parameter ranges that might be expected at undisturbed sites:

- For each soil quality parameter, determine which values can be considered "typical" for unimpacted forested regions of northeastern Ontario.
- Establish whether the values at the reference sites are within the range established in the previous step.
- Use reference values to determine numerical parameter ranges representing low to no impact, moderate impact, and severe impact for each soil quality parameter.

The following steps were taken to rank the test sites:

- Compare the soil quality parameters at each test site to the reference parameter ranges to assign an impact rank for each parameter (low, moderate, severe).
- Use best professional judgment to give each site an overall ranking based on the rank for soil development (Step A), and adjusted according to the ranks for the other categories of soil quality parameters (Step B).

Based on the above evaluation of soil quality parameters, each test site was placed into one of three categories:

Rank		**Description**
Green	Low to No Impact	The majority of the soil quality parameters at these sites fell within the "green" parameter range. The soil can be considered a good medium for plant growth.
Yellow	Moderately Impacted	The majority of the soil quality parameters at these sites fell within the "yellow" parameter range. Selected soil quality parameters appeared to be affecting the performance of the soil as a medium to promote plant growth.
Red	Severely Impacted	The majority of the soil quality parameters at these sites fell within the "red" parameter range. Some soil quality parameters appeared to be seriously impacting soil potential and were likely limiting plant growth.

These steps are further discussed in the following sections.

3.4.2 Reference Site Evaluation

To determine whether the soil quality parameters measured in the reference site soils could be considered indicative of undisturbed northern Ontario sites, a detailed literature review was undertaken by researchers at MIRARCO (Mining Innovation, Rehabilitation and Applied Research Corporation), Laurentian University. The report, provided by MIRARCO, detailing background soil quality and fertility levels for typical northeastern Ontario forested sites is documented in Appendix GD-9-1. The literature review revealed that, although little information exists related to the typical soil chemical and physical conditions in the Sudbury region, the reference sites were not nutrient deficient when compared to other northeastern Ontario soils formed on similar parent materials with similar forest cover.

Next, numerical ranges were established for each soil quality parameter. These ranges were based on regionally representative values from the literature review, the reference sites and on best professional judgement.

Once the parameter ranges had been established, the soil quality parameters at each reference site were compared to the ranges. Although the reference site parameter values were considered in the formation of the ranges as discussed above, the variation between the reference site conditions made it necessary to confirm that all of the reference sites could indeed be considered indicative of “typical” unimpacted Sudbury soils or northeastern Ontario conditions. Double-checking the reference site values against the established parameter ranges increased confidence in the use of the reference site values.

The results revealed that overall the three reference sites ranked green, indicating that the physical and chemical soil characteristics present at the sites were typical of forested areas of northeastern Ontario and were representative of conditions conducive to plant growth.

Table 3.21 shows the ranges established for each soil quality parameter. Detailed information that provides the rationale used to develop these ranges is provided in Appendix GD9-2.

Table 3.21 Summary of Soil Chemistry Parameter Ranges for Test Site Evaluation and Ranking

Rank	Low Quality Soil (Red)	Moderate Quality Soil (Yellow)	High Quality Soil (Green)
Organic Matter (g/100g)			
Total C	<3	3-3.9	>3.9
Total N	<0.1	0.11-0.21	>0.22
Soil Exchange Complex Chemistry (cmol(+)/kg)			
Cation Exchange Capacity	<19	20-24	>25
Calcium	<0.24	0.25-0.39	>0.4
Magnesium	<0.1	0.1-0.15	>0.15
Ca:Mg Ratio	<1.4	1.5-2.9 or >6	3-5.9
Base saturation (%)	<1.9	2-4.9	>5
Fertility (mg/kg)			
N as Ammonium	<0.19	0.2-0.39	>0.4
Extractable P	<5	5-7.9	>8
Extractable K	<44	45-64	>65
Extractable Fe	<499	500-749 or >1,800	750-1,800
Extractable Mn	<10	10-24 or >200	25-200
Fe:Mn	<5	5-14 or >50	15-50
Extractable Mg	<15	15-25	>25

3.4.3 Test Site Evaluation

Each of the test sites was evaluated and assigned an impact rank based on soil chemistry. To achieve this, the soil quality results at each of the test sites were compared to the parameter ranges provided in Table 3.21. A qualified soil scientist with experience in the Sudbury region (Dr. Graeme Spiers, Mirarco, Laurentian University) evaluated the site results and gave each site its final rank. The absolute numbers for each soil quality parameter as well as the comparison between the test site and reference ranges were assessed. Dr. Spiers took into consideration soil development, which includes soil texture and the presence of soil horizons. A summary of the final site ranking for each of the test sites is shown in Table 3.22. A detailed description of the rationale for the overall soil LOE ranking can be found in Appendix GD9-2: Soil Characterization LOE Ranking Report.

Table 3.22 Summary of Overall Test Site Ranking Based on Soil Chemistry Parameters

Site	Rank	Distance from Associated Smelter
CC-01	Yellow	Copper Cliff 5.3 km
CC-02	Red	Copper Cliff 5.7 km
CC-03	Red	Copper Cliff 2.7 km
CC-04	Yellow	Copper Cliff 6.8 km
CC-06	Yellow	Copper Cliff 8.4 km
CC-07	Yellow	Copper Cliff 8.3 km
CC-08	Yellow	Copper Cliff 16.6 km
CON-01	Yellow	Coniston 24.8 km
CON-02	Red	Coniston 2.1 km
CON-03	Yellow	Coniston 5.7 km
CON-05	Yellow	Coniston 8.9 km
CON-06	Yellow	Coniston 1.8 km
CON-08	Red	Coniston 2.1 km
FB-01	Yellow	Falconbridge 5.1 km
FB-02	Green	Falconbridge 10 km
FB-03	Yellow	Falconbridge 20.9 km
FB-05	Yellow	Falconbridge 3.5 km
FB-06	Green	Falconbridge 14.7 km

The majority of the test sites were ranked as moderately impacted (yellow), indicating that at least some of the soil quality parameters measured at these sites were limiting plant growth. There were sites on both the Copper Cliff and Coniston transects that were ranked severely impacted, indicating that the growing conditions at these sites were unlikely to support healthy plant growth. Two sites on the Falconbridge transect were ranked low to not impacted, indicating that the soil conditions at these sites were comparable to the conditions at the reference sites.

3.5 Plant Community Assessment: Methods and Results

The plant community assessment was a comprehensive survey that consisted of measuring numerous ecological variables at each site. The data used in Step 1 of the evaluation of the Plant Community Assessment are presented in Section 3.6. An overview of the plant community assessment methodology is presented in the following sections. Detailed field methods are provided in Appendix GB Protocol No.6.

3.5.1 Defining a Self-Sustaining Forest Ecosystem

To assess relative impact on vegetation at the test sites, it was first necessary to establish a reference for comparison. A definition of a self-sustaining forest ecosystem was developed to create a reference base from which to assess impact. This definition is provided below.

A self-sustaining forest ecosystem is an assemblage of plants, with a treed overstory, that occurs with a degree of predictability for any given time since disturbance on any given topographic position, soil type and aspect within a climatic zone.

In self-sustaining forest communities, ecosystem processes and functions such as energy flow, production, nutrient cycling, reproduction, regeneration and decomposition are not impaired. Topography, soil structure, texture and nutrients are important determinants of species composition and forest structure.

The structural and functional components of a natural regional forest ecosystem are predictable. They include the complexity of the tree, shrub and ground layers that provide habitat for mammals, birds and invertebrates. Topography, soil structure, texture, nutrients and moisture are important determinants of species composition and forest structure. Studies have assessed the rate of community development in forested regions after effects such as fire, logging and erosion and have reported that in a system where soils are not impairing regeneration, the forest canopy can be closed (i.e. tree crowns touch) 30 years after the event has ceased (Chambers, 1995). At eroded sites, providing the erosion has ceased, and other limiting factors such as moisture or seed source are not impeding recovery, a well-established plant community could regenerate two years after the event. It stands to reason that a self-sustaining plant community in the Sudbury region could have established along a predictable pattern to maturity following an intermittent or catastrophic event, such as fire, windstorm, beaver disturbance, insect infestation or other natural events. The approach used to rank the plant community data considered in part whether the site was regenerating along this predictable pattern. The metal levels, low pH and erosion identified at some of the test sites represent ongoing perturbations, which can interrupt a predictable pattern of vegetation recovery. At these sites, once a plant community becomes established, it may be dominated by acid and metal tolerant species.

3.5.2 Approach

The terrestrial plant community assessment was directed by Dr. Peter Beckett from Laurentian University and an independent senior ecologist (Maureen Kershaw, Ph.D candidate) from the Sudbury region. Both parties had extensive knowledge of the local flora and were able to use their best professional judgment to establish a “snapshot” of the site conditions at the time of the survey. Most of the surveys were conducted in August and early September of 2004, with some additional work done in the summer of 2005.

At each site, a 100 m x 100 m square plot was established and the site characteristics were recorded. The size of plot was similar to those established by Natural Resources Canada to monitor the effects of acid precipitation and, more recently, climate change. The plots were large enough to include some of the natural variability that occurs in the Sudbury Region, where plant distribution is often clumped and interspersed with forest openings on rocky outcrops. At the same time, the plot was placed where site conditions and plant cover were relatively uniform in terms of dominant tree cover, mode of deposition, range of soil depth, terrain and stoniness. The 100 m x 100 m plot size optimized the sampling effort and permitted the site description to refer to relatively uniform site conditions in forested ecosystems. The plot was also established with a perimeter buffer strip of at least 10 m to avoid edge effects from roads, agricultural areas or other potentially influencing factors. Sub-sampling units were established to record species presence and cover in the understory, ground cover and downed woody debris. These data are described in more detail in subsequent sections.

Each site was classified by ecosite. Historical vegetation damage in the region precluded the use of standard provincial vegetation classification systems, such as “*The field guide to forest ecosystems of Central Ontario” SCSS Field Guide FG-01 (1997).*” This provincial forest ecosystem classification system was developed from data collected from “undisturbed” mature forests and is not effective in classifying communities in early or intermediate successional stages or those disturbed by anthropogenic activities. The same format for nomenclature was adopted to name the ecosite types and the plant communities: dominant overstory species, dominant understory species and a terrain modifier. Linkages were also made to earlier plant community classifications for the Sudbury area completed by Amiro and Courtin (1981), James and Courtin (1985), Sinclair (1996) and others. A variety of key ecological parameters were measured at each site to support the classification.

There were five major components to the field work performed for the plant community assessment, each of which is described in more detail in the following sections:

- Broad plant inventory;
- Percent cover assessment;
- Detailed tree and tall shrub assessment;
- Coarse woody material assessment; and
- Ecosite classification.

3.5.3 Methods

An overview of the methods used to collect each of the five components is presented in the following sections. The detailed field protocol containing the methods is provided in Appendix GB-6

3.5.3.1 Broad Plant Inventory

The aim of the broad plant inventory was to produce a detailed list of plant species growing at each site. The parameters measured included species from the following groups:

- trees;
- tall shrubs;
- low shrubs;
- herbs;
- graminoids;
- ferns and fern allies; and
- bryophytes and lichens.

Any unknown species were collected and keyed out in the lab using Gleason and Cronquist (1991), Soper and Heimburger (1990 3rd printing), Dore and McNeill (1980) for grasses; Cody and Britton (1989), Crum (1976) for bryophytes; and Brodo and Sharnoff (2001) for lichens, with reference checks with herbarium specimens. The presence of all species was recorded within a 10 m width along four 50 m transects radiating north, east, south and west from the central staked area. The design increased the probability that the survey covered the range of local site conditions that occurred in the plot, with a total surveyed area of approximately 2,000 m^2.

A schematic of the site area, which was examined during the broad plant inventory, is shown in Figure 3-18. Photographs were taken from the central stake, halfway down each transect and facing back up the transect (Appendix GC).

3.5.3.2 Percent Cover Assessment

The aim of the percent cover assessment was to collect quantitative information about the relative abundance of a variety of plant species and site conditions. To assess the percent cover, a 25 m transect was established from a northeast to southwest direction over the staked area. Again, the transect design was used rather than a square format to increase the probability of describing the range of plant community conditions that occurred at the site. This design is a standard approach on terrain that consists of a mosaic of variable soil depths over bedrock or variable conditions. Square or circular plots are more common in areas of uniform conditions. Along this transect, twenty-five 1 x 1 m square quadrats were established; the one meter square quadrat size is the standard for assessing the bryophyte/lichen, herb and low shrub layers (Brower et al., 1997). In each quadrat, the following parameters were measured:

- The percentage cover of each plant species present in the quadrat (adult trees and tall shrubs were generally not included in this assessment); and
- The percentage ground cover of non-vegetative substrate, including bedrock, gravel/cobbles, bare soil, leaf litter, surface crusts and woody debris (<7.5 cm in diameter pieces), to the nearest 5%.

The presence of any patterned ground (e.g., frost-induced gravel polygons) was also noted.

A schematic of the site area, which was examined to establish the percent cover, is shown in Figure 3-18. Some of the quadrats were photographed (quadrats #0, 4, 9, 14, 19, and 24 starting from the NW corner, unless otherwise noted) (Appendix GC).

3.5.3.3 Detailed Tree and Tall Shrub Assessment

The aim of this survey was to collect quantitative information on the tree and tall shrub populations at each site. At both ends of the 25 m transect used to determine the percent cover assessment, a 10 m x 10 m plot was established to record the trees and shrubs existing at the site (Figure 3-18). This is the standard plot size for assessing tall shrubs and trees (Brower et al., 1997). Within each plot, the following parameters were assessed:

- All species were identified;

- The strata (canopy or understory) were identified for each species;
- The number of specimens from each species and strata was counted;
- The percentage cover for each species in both strata was estimated;
- The average height for each species was estimated; and
- The average diameter at 30 cm and diameter at breast height (DBH) for each species was recorded.

In addition, a separate, thorough assessment of the mortality and percentage dieback for trees and tall shrubs was conducted in the summer of 2005. For this assessment, a 10 m x 10 m plot was established 25 m northeast of the stake, and another plot 25 m southwest of the stake. The plot locations were adjusted slightly to ensure that they fell within the dominant ecosite type for the site. The following parameters were collected in each plot:

- The total percent tree cover in the plot;
- Identification of all species in the plot;
- The growth form (i.e., single-stem vs. multi-stemmed) for each species;
- The height of each tree;
- Estimation of the % crown mortality;
- The number of dead stems (per clump if growth form was coppiced);
- The number of live stems (per clump if growth form was coppiced); and
- Any snags present at the site were noted, with the species identified.

3.5.3.4 Assessment of coarse woody material

The coarse woody material at the site was assessed along a transect established from the southwest to the northeast corner of the initial 10 m x 10 m tree and shrub assessment areas (Figure 3-18). Along each transect, each stump or piece of downed woody debris greater than 7.5 cm in diameter was recorded in terms of the following:

- Species (if possible);
- Length;
- Diameter; and
- Degree of decomposition.

The degree of decomposition was established using decay classes developed in Sollins (1982). This system is based on a rating of one to five, where:

1. intact, fine branches present, needles/leaves present
2. fine branches and foliage absent, round in cross section
3. branches gone, bark (except white birch) gone, partially decomposed
4. friable, oval, contact with the ground
5. highly decomposed, more than 50% integrated as surface organics

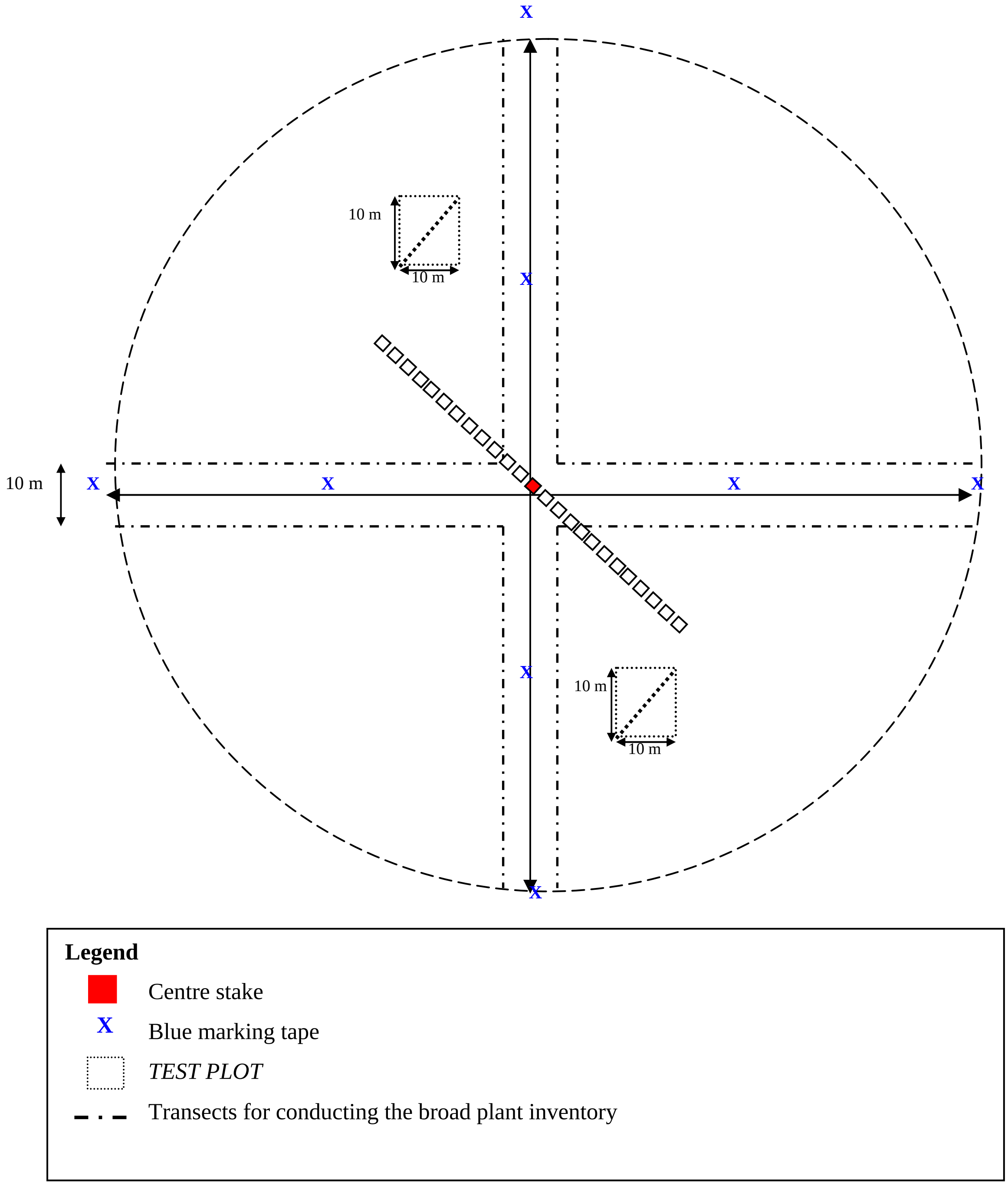


Figure 3-18 Schematic Diagram of Plots for Estimating Count, Average Height and Percent Cover of Tree and Tall Shrub Species, Assessment of Coarse and Downed Woody Debris and for the Broad Plant Inventory

3.5.3.5 Ecosite Classification

During the summer of 2005, each site was classified according to the dominant plant community present. The following information was collected at each site:

- Terrain (level, undulating, rolling, hilly), and an estimate of the average % slope;
- Soil depth (very shallow <10 cm, shallow 10-30 cm, moderately deep 30-60 cm, deep >60 cm);
- Soil type according to textural analysis (loam, silt loam, loamy coarse sand, etc.);
- Percentage cover of exposed bedrock;
- Dominant understory, including dominant species of tall shrub, low shrub (note also presence/absence of blueberry species), herbaceous, pteridophyte, graminoid, bryophyte (note also presence/absence of Polytrichum species), and lichen (note also presence/absence of Cladina species);
- Dominant overstory, with species composition; and
- Percentage canopy cover category (<30%, 30-50%, 50-70%, >70%), along with a visual estimate of actual percentage.

Using the above information, an ecosite description was provided for the site, including a subdominant community where necessary. The communities were named based on the dominant overstory, dominant understory, and a description of the terrain. The parameters measured are those used by the Ontario Ministry of Natural Resources Ecosytem Classification System (Chambers et al., 1997).

3.5.4 Results

A large quantity of data was collected during the plant community survey. This information was analyzed in a variety of ways to gain an overall ranking for each site (this process is described further in Section 3.6). In the following sections, the location of the raw data from each of the five study components is provided and, a summary of the results is also presented.

3.5.4.1 Broad Plant Inventory

The results and tally sheets for each site are provided in Appendix GE-2-1, Tally Sheet 1. In total, 297 plant species (31 ferns and fern allies, 26 grasses and sedges, 109 herbaceous species, 29 lichen, 28 low shrubs, 26 mosses, 30 tall shrubs and 18 tree species) were identified. The number of species at the test sites ranged from 21 to 82, and the number of species at the reference sites ranged from 57 to 89. A summary of the number of species present at each site is provided in Table 3.23.

Table 3.23 Summary of the Number of Species at Each Test Site for the Broad Plant Survey for the Plant Community Assessment LOE

Site	Ferns and Fern Allies	Grasses and Sedges	Herbaceous	Lichens	Mosses	Low Shrubs	Tall Shrubs	Trees	Total Species
CC-01	1	3	9	14	7	6	4	5	49
CC-02	0	4	0	11	3	4	1	7	30
CC-03	0	4	0	7	4	2	0	4	21
CC-04	2	5	11	6	7	5	9	8	53
CC-06	6	4	17	13	9	7	12	4	72
CC-07	6	5	10	12	7	7	7	7	61
CC-08	6	9	18	20	8	6	6	9	82
CON-01	3	2	11	10	6	4	5	6	47
CON-02	2	5	6	13	7	5	4	4	46
CON-03	4	6	9	12	8	6	9	4	58
CON-05	3	4	6	15	7	5	10	5	55
CON-06	3	12	13	17	7	5	4	7	68
CON-07[a]	2	8	29	20	7	1	7	6	80
CON-08	2	4	7	15	2	3	3	5	41
FB-01	2	1	1	2	2	4	2	6	20
FB-02	5	2	10	11	8	6	6	7	55
FB-03	5	1	8	17	11	9	6	6	63
FB-05	2	3	5	9	3	2	3	7	34
FB-06	1	3	5	18	10	5	2	8	52
REF-02	5	3	13	8	7	6	8	7	57
REF-03	4	6	26	1	10	7	13	6	73
REF-04	4	3	13	22	15	11	12	9	89

[a] This site was historically limed and replanted. The pH is consequently much higher than the other test sites. It is not considered in the final site rankings but is discussed in greater detail in Section 3.14.2.

Figure 3-19 illustrates the trend of species richness versus distance from the nearest smelter. The number of plant species present at the sites closer to the smelters was generally lower on the Copper Cliff and Falconbridge transects than for sites farther away. This trend was not observed with the Coniston transect. The lack of relationship at the Coniston sites may be a result of the low total metal levels in the soils and/or other factors such as soil erosion, etc. A similar pattern was also observed with other plant community variables (see Appendix GE-4-C for more details) with distance from the smelter such as:

- Some plant groups: for example, lichens, bryphytes, herbs, low shrubs, and tall shrubs. There was no relationship for the number of gramminoid species or number of trees and distance to the smelter;
- Substrate analysis: there was a higher percentage of bare rock and soil near the smelters;
- Reestablishment of good condition lichen and moss species: there are lower numbers near the smelters which indicate that the current conditions are not suitable to support these species and,
- Leaf litter: there is a lower percentage of leaf litter close to the smelters which is a component of soil fertility.

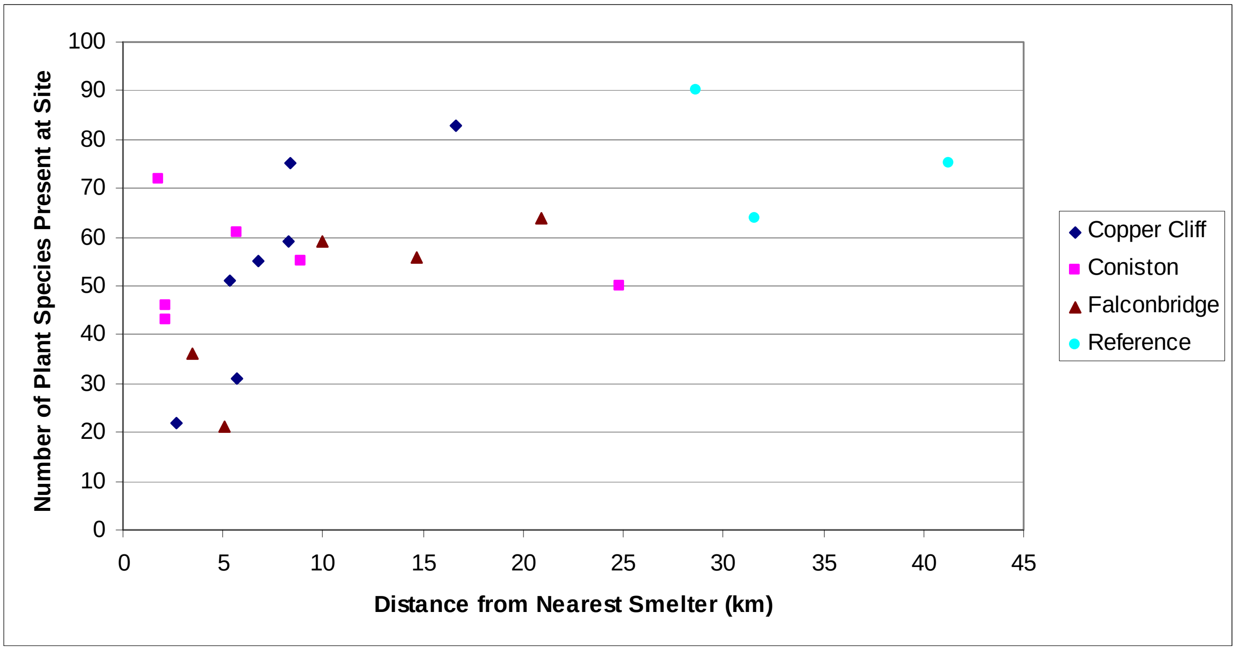


Figure 3-19 Species richness at test and reference sites plotted against distance from the nearest smelter. Data for CON-07 is not shown since it was historically limed and replanted (for more detail on site CON-07, see Section 3.14.2)

Along the Copper Cliff transect there was a noticeable difference in species presence from site to site. There were no ferns, fern allies or herbaceous plants observed at CC-02 or CC-03. While at CC-06, CC-07 and CC-08 there seemed to be a better representation of species from all groups. The number of tree species observed along this transect ranged from four at CC-03 and CC-06 to nine species present at CC-08. Lichens and mosses had the greatest species richness at all sites except for CC-04. At CC-04, herbaceous plants and shrubs had the greatest species richness.

Plant species that were considered acid-metal tolerant were also categorized at each site. The list of acid-metal tolerant species is provided in Appendix GE-4-A. This species list is meant as a guide only as some plant species can develop genetically tolerant strains in response to acid and metal stress. The ERA did not examine genetic tolerance to metals. Sites along the Copper Cliff transect had an average of 13 acid-metal tolerant indicator species (range from 10-18).

The Coniston transect had a greater representation of plant types at all sites. Lichens and mosses had the greatest species richness at all sites except for CON-07 (the historically limed and re-greened site), where there were more herbaceous plant species. The number of tree species observed along the Coniston transect ranged from four to seven; CON-06 had the highest number of tree species. Sites on the Coniston transect had an average of 13 acid-metal tolerant indicator species (ranging from 8 indicators at CON-01 to 17 at CON-06).

The distribution of plant species was different at the Falconbridge sites compared to the other two transects. Although at the lichens and mosses generally had the greatest species richness, the numbers of grass and sedge and herb species were less than at Copper Cliff and Coniston. The number of tree species observed was similar to the other two transects where the range was between six (FB-01/FB-03) and eight (FB-06) species. Sites on the Falconbridge transect had an average of 10 acid-metal tolerant indicator species (ranging from 5 indicators at FB-02 to 14 at FB-03).

The reference sites were generally similar to the test sites in their distribution of plant species, with herbaceous plants, lichens and mosses and shrubs having the greatest species richness. The number of tree species was similar to the other three transects with 6-9 three species recorded at the three reference sites. The average number of acid-metal tolerant indicator species at the reference sites was 7 (ranging from 4 indicators at REF-03 to 10 at REF-04).

The greatest species richness was observed at REF-04 with almost 90 different species recorded, while FB-01 had the least with only 20 species present. The ranges for the three transects are as follows: 21 to 82 species along the Copper Cliff transect; 41 to 80 species at Coniston; and 20 to 62 different species at Falconbridge. At the three reference sites, the total number of species present ranged from 58 to 89. The historically limed site (CON-07) stands out as having the greatest species diversity along the Coniston transect.

3.5.4.2 Percent Cover Assessment

A selection of the quadrats was photographed (usually the quadrats photographed were #0, 4, 9, 14, 19, and 24 starting from the NW corner, unless otherwise noted). These photographs are available in Appendix GE-1, and the tally sheets from each site are available in Appendix GE-2-2, Tally Sheet 2.

3.5.4.3 Detailed Tree and Tall Shrub Assessment

The results of the detailed tree and tall shrub assessment are provided in Appendix GE-2-3, Tally Sheet 3a. In general, the more productive a site, the greater the density of trees found at the site. For instance, the height of planted and natural pine, spruce and other trees on the site reflects the productivity of the site. Additionally, the degree to which red maple, red oak and white birch have broken through the multistemmed stunted coppice growth into tree forms with a single dominant stem also reflects improvements in site productivity.

3.5.4.4 Percent Mortality and Dieback

The results of the percent mortality and dieback survey are provided in Appendix GE-2-3, Tally Sheet 3b. This assessment measures the mortality and dieback in red maple, white birch and red oak, which is a reflection of the stage of recovery of the ecosystem.

3.5.4.5 Coarse Woody Material Assessment

The coarse woody material assessment is a measure of downed woody debris at the site. The results of the coarse woody material assessment are provided in Appendix GE-2-4, Tally Sheet 4. This measure is important because it indicates suitable seedbeds for many native species and, returns organic matter into the ecosystem providing a niche for microflora and fauna, which are indicators of healthy ecosystems.

3.5.4.6 Ecosite Classification

The ecosite classification provides a common language ecosystem classification description for each site that is recognizable by ecologists familiar with the Ecological Land Classification (ELC) system. The results of the ecosite classification can be viewed in Appendix GE-2-5, Tally Sheet 5. The ecosite classification provides a succinct description of the ecological community present at each site. The results are provided in Table 3.24.

Table 3.24 Summary of the Composition of Dominant and Subdominant Ecosite Communities for Test and Reference Sites

Site	Dominant Ecosite Community (% of site)	Subdominant Ecosite Community (% of site)
Reference Sites		
REF-02	White birch-balsam fir / bracken fern deep loam community (100)	N/A
REF-03	Red pine / fly honeysuckle shallow loam community (60)	Poplar lowland community (40)
REF-04	Red pine / blueberry–bracken fern moderately deep silt loam plain community (100)	N/A
Test Sites		
CC-01	White birch / *Pohlia nutans* loam barrens community (100)	N/A
CC-02	White birch / red maple bedrock transition (savannah) transition community (100)	N/A
CC-03	White birch / bedrock transition community (100)	N/A
CC-04	White birch / *Deschampsia flexuosa* bedrock (savannah) transition community (70)	Poplar lowland silt loam community (30)
CC-06	White birch / *Deschampsia flexuosa* bedrock (savannah) transition community (51)	Poplar lowland silt loam community (49)
CC-07	White birch / blueberry / sweet fern / *Deschampsia flexuosa* bedrock (savannah) transition community (75)	Sheep laurel lowland community (25)
CC-08	White birch / blueberry / sweet fern / *Deschampsia flexuosa-Lycopodium* bedrock (savannah) transition community (51)	Poplar silt loam lowland community (49)
CON-01	Red oak-white birch / blueberry-hilly fine sandy loam community (100)	N/A
CON-02	White birch / blueberry/ *Pohlia nutans* silt loam transition forest community (100)	N/A
CON-03	White birch / *Deschampsia flexuosa* shallow silt loam community (100)	N/A
CON-05	Red pine / *Deschampsia flexuosa* - sweetfern silty clay loam savannah transition (60%)	Trembling aspen / *Deschampsia flexuosa* lowland community (40%)
CON-06	White birch very shallow silt loam bedrock barrens community (100)	N/A
CON-08	*Deschampsia cespitosa / Pohlia nutans* mixed bedrock- silt loam soil barrens community (100)	N/A
FB-01	White birch-red oak / blueberry loam savannah transition community (100)	N/A

Table 3.24 Summary of the Composition of Dominant and Subdominant Ecosite Communities for Test and Reference Sites

Site	Dominant Ecosite Community (% of site)	Subdominant Ecosite Community (% of site)
FB-02	White birch / bracken fern-large leaf aster silt loam community (51)	Poplar lowland community (49)
FB-03	Jack pine-sheep laurel / *Polytrichum* very shallow silt loam plain community (100)	N/A
FB-05	Mixed white birch / red pine fine sandy loam plain community (100)	N/A
FB-06	White birch - red maple / blueberry shallow loam community (100)	N/A
Limed Site		
CON-07	Balsam poplar / *Lotus corniculatus*-graminoid silt loam transition community (100)	N/A

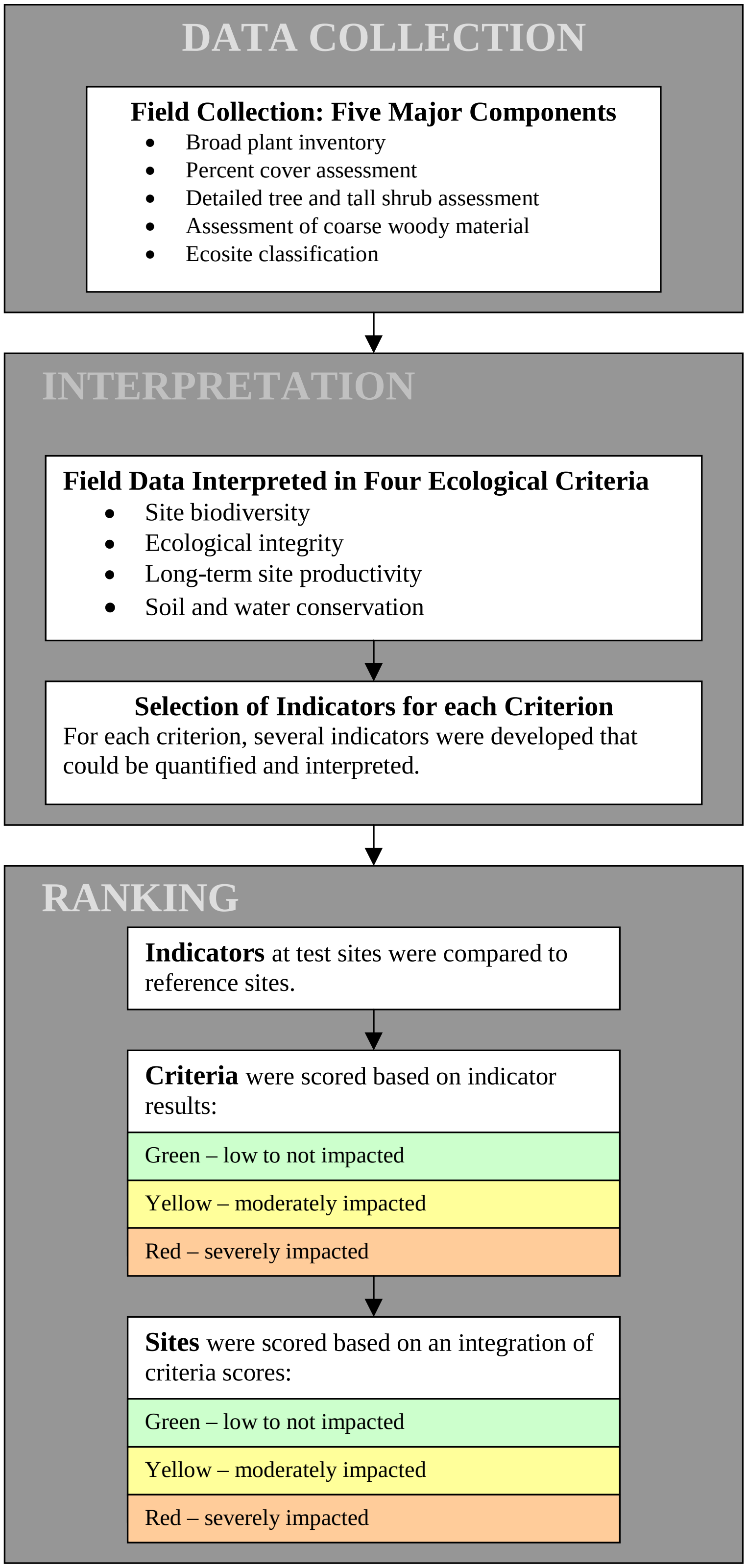
N/A = Not applicable, where the dominant vegetation type makes up 100% of the community, there is no subdominant community

3.6 Plant Community Assessment LOE (Step 1)

The plant community assessment provides a compelling line of evidence for the ERA. The living vegetation that exists at a site reflects the total integration of all site conditions (*i.e.*, climate, soil quality, physical and chemical characteristics). The objective of this LOE was to provide detailed documentation of the relative condition or diversity of the plant community at each test site by comparing them to the reference sites.

The report, “Plant Community Assessment Ranking Report” (Appendix GE-4) provides a detailed description of the results and approach used to determine an overall ranking for each site in this LOE. Although the historically limed and regreened site, CON-07, is not included in the final ranking, it is included in this report for comparative purposes. A comparison between CON-07 and CON-08 and the effect of historic liming and re-greening is presented in Section 3.14.2. The ranking scheme is presented in Figure 3-20 and is described the following sections.

For the purposes of the plant community assessment, all information regarding the soil metal levels and other soil chemistry was deliberately not provided to those team members responsible for the interpretation of the ecological data in order to reduce the potential for bias in the plant community assessment.



Field Collection: Five Major Components

- Broad plant inventory
- Percent cover assessment
- Detailed tree and tall shrub assessment
- Assessment of coarse woody material
- Ecosite classification

Field Data Interpreted in Four Ecological Criteria

- Site biodiversity
- Ecological integrity
- Long-term site productivity
- Soil and water conservation

Selection of Indicators for each Criterion

For each criterion, several indicators were developed that could be quantified and interpreted.

Indicators at test sites were compared to reference sites.

Criteria were scored based on indicator results:

Green – low to not impacted

Yellow – moderately impacted

Red – severely impacted

Sites were scored based on an integration of criteria scores:

Green – low to not impacted

Yellow – moderately impacted

Red – severely impacted

Figure 3-20 Final Ranking Scheme for Plant Community Assessment

3.6.1 Overview of Ranking Approach

An evaluation approach was developed by the SARA Group to consider and rank the plant community data. A criterion and indicator framework was developed for this LOE, and the plant community results were evaluated in terms of four ecologically significant criteria:

- ***Site Biodiversity***: This criterion provides a snapshot of the number and distribution of species in the community. As such, it provides a biological index of the current overall status of the community. It does not provide any evaluation of the "quality" of the community in terms of the integrity of the species present or the presence/absence of all components in the community, nor does it provide a strong indication of the sustainability of the ***community*** over time. However, it can act as a rough estimate of the resilience of the community to stresses.

- ***Ecological Integrity***: This criterion provides an index of the number of different species present in the community and their growth habits. For example, ecological integrity takes into consideration the presence or absence of invasive species, the presence or absence of acid-metal tolerant indicator species, and the presence or absence of a skewed species distribution, thereby providing an indication of potentially unusual site conditions. This criterion measures the completeness of the community and the integration among the parts.

- ***Long-term Productivity:*** This criterion takes into consideration how well species are growing on a site and considers whether this growth is sustainable into the future. For example, the indication of stressors, such as insects and disease, are considered. In addition, long-term productivity provides insight into the actual growing capacity of the site as reflected in a surrogate for biomass production (height of trees, density of trees and shrubs). It also provides an indication of the availability of organic debris in the community, which provides a slow release of organic-based nutrients.

- ***Soil and Water Conservation:*** This criterion reflects the integrity of the growing medium at the site. In addition, assessment of this criterion provides an indication of the degree to which water is held on the site to support growth. The properties of the soil define regeneration success potential by promoting or limiting plant growth. The character of the soil is critical for sustaining the community over time.

The selection of these criteria was based on the biological criteria defined by the Canadian Council of Forest Ministers to measure Canada's progress in the sustainable management of its forests (CCFM, 1995) as well as the criteria used to assess biodiversity within Canada's biodiversity strategy, a framework adopted by national and provincial parks and protected areas (Environment Canada, 1995).

A number of indicators were assigned to each of the four criteria (Figure 3-21). Links between criteria were defined and, in some cases, indicators addressed multiple values under different criteria. The indicators were selected because they were considered to be good descriptors of the relative status of the community with respect to the criteria, they were easily measured, and they could be used for future monitoring of changes to communities. It was also important that the criteria were comprehensible to the informed public and to policy makers.

The rationale for the use of these indicators, and detailed results of this evaluation are contained in the report in Appendix GE-4.

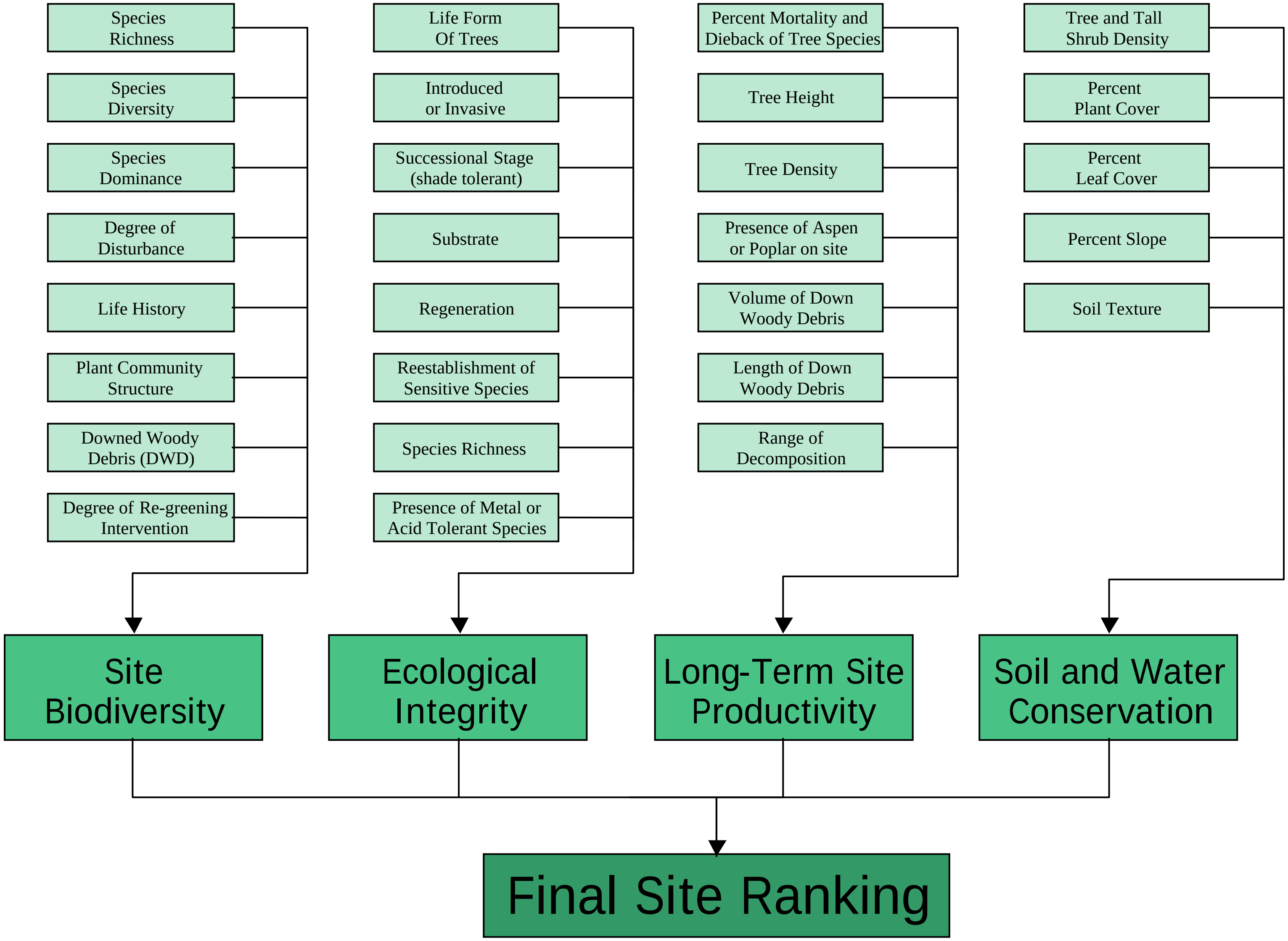


Figure 3-21 ERA Framework Developed to Rank Results in terms of Four Ecologically Significant Criteria

The application of ranking followed a step-wise process:

1. Indicators were selected to represent four ecological criteria: site biodiversity; ecological integrity; long-term site productivity; and soil and water conservation.
2. The indicator results were calculated for each site and compared to the reference sites. A rank was assigned for each indicator at each site. The ranking process differed between indicators and the details of each indicator's ranking process are presented in Appendix GE4-B.
3. Using best professional judgment, a rank was given to the criterion, based on the associated indicator ranking results. Ecology experts considered the ranks given to the indicators, as well as their impression of the condition of the site to assign criteria ranks.
4. Once all criteria were ranked for each site, each test site was evaluated using best professional judgment to determine whether it was impacted or not. For the purposes of evaluating the results of the plant community assessment, each site was ranked as follows:

Rank		Description
Green	Low to not impacted	The site was representative of a complete forest ecosystem in that ecodistrict of Ontario.
Yellow	Moderately impacted	The site was not representative of a complete forest ecosystem. It was an ecosystem in transition and was showing signs of recovery or decline.
Red	Severely impacted	The site was not at all representative of a complete forest ecosystem, and showed very few signs of recovery.

3.6.2 Reference Site Evaluation

This evaluation determined whether the ecological community at each reference site could be considered "typical" of the Sudbury region and self-sustaining. This step determined whether the reference sites could be used as comparisons for the test sites. If the plant community present at a reference site was considered natural of the region and self-sustaining, then it could be used for comparison to determine whether a test site plant community was impacted.

Each reference site was evaluated in terms of the ecological criteria and indicators to determine whether it represented the range of plant communities typifying the Ministry of Natural Resources Ecodistricts. The Sudbury region covers three ecodistricts. The northwestern part of the city is in Ecodistrict 4E-3; the northeastern part of the city is in Ecodistrict 4E-4; the central and southern portions of the city are located in Ecodistrict 5E-4. The ecosite classifications for the reference sites are provided in Table 3.24.

Detailed results of the indicator analysis and site-specific discussion of the reference sites are provided in Appendix GE-4C and Appendix GE-4D.

As described in the Plant Community Assessment Ranking Report in Appendix GE-4, evaluation of the reference sites showed them to be satisfactory comparison sites for the range of plant communities typifying the Ministry of Natural Resources Ecodistrict 5E-4. This Ecodistrict is a transitional vegetation zone where boreal jack pine, balsam fir and spruce forest elements mix with Great Lakes St. Lawrence Forest hardwoods and mixed-forest elements. The reference sites do emphasize that not every indicator had to be rated high for a plant community to be natural and self-sustaining.

3.6.3 Test Site Evaluation

Detailed results of the indicator analysis, individual criteria and indicator ranking results and site-specific discussion of the test sites are provided in Appendix GE-4. Final site rankings for the plant community assessment LOE are provided in Table 3.25. This historically limed site (CON-07) was not included in the site ranking but is discussed in Section 3.14.2.

Table 3.25 Summary of the Overall Site Ranking for the Plant Community Assessment LOE

Site	Rank
CC-01	Red
CC-02	Red
CC-03	Red
CC-04	Red
CC-06	Yellow
CC-07	Red
CC-08	Red
CON-01	Yellow
CON-02	Red
CON-03	Yellow
CON-05	Red
CON-06	Red
CON-08	Red
FB-01	Red
FB-02	Green
FB-03	Yellow
FB-05	Yellow
FB-06	Yellow

The evaluation revealed that the test sites contained a diversity of plant communities. The majority of the test sites were ranked severely impacted, indicating that the plant community was not at all representative of a complete forest ecosystem and showed very few signs of recovery. Some sites were ranked moderately impacted, indicating that the site was not representative of a complete ecosystem but was an ecosystem in transition, showing signs of either recovery or decline. There was only one test site (FB-02) where the plant community was considered similar (low impact) to the reference sites.

3.7 Toxicity Testing: Methods and Results

The toxicity testing approach and results are outlined in the following section. The SARA Group used a phased approach to toxicity testing with the progression and formulation of each step dependent on the results of the previous phase. The initial steps identified the battery of test species to be used in the toxicity tests. These species were then grown in all of the test and reference site soils and the results were used in the ranking of the toxicity line of evidence.

3.7.1 Approach

Ecological communities are an aggregation of populations consisting of all plants, animals and microbes that occur in the same time and place and that interact physically, chemically and/or behaviourally. Although the community itself is what the risk managers ultimately aim to protect, it is not possible to study all components of the ecosystem. Representative species must be selected because it is not possible or desirable to perform toxicity testing on all species in the community. Doyle *et al*. (2003) suggested that plants and soil dwelling organisms might be more at risk to atmospheric emissions from smelters than wildlife. Therefore, it was important to address soil toxicity to these groups of organisms as part of this risk assessment.

The objective of the toxicity testing LOE was to assess the performance of test species in soils from the test and reference sites. The rationale for conducting toxicity testing was that the soils in Sudbury contain more than one metal and the soil pH is below the range addressed in the generic MOE soil criteria (MOE, 1997). By conducting toxicity testing in soil collected from the sites it was possible, under standardized laboratory conditions, to determine whether the soil was toxic to plant and invertebrate test species irrespective of other environmental conditions (microclimate, moisture, depth to bedrock, etc.). This testing in “natural” soil from the site (soil collected from the site but not amended in any way) was used to rank the soil toxicity LOE.

All of the selected reference and test sites had soil pH levels between 4 and 5. Although a range of this magnitude is small in terms of the variety of site conditions that can exist in natural systems, it can be large in terms of the ability of species to grow and survive in the site soil. A pH of less than 5 is known to be limiting for growth in some plants and survival in some invertebrates (e.g., Troeh and Thompson, 2005; Winterhalder, 1995). Concurrent to the testing in natural soil, tests were also completed using pH-amended soil (soil collected from the site and the pH raised to a standardized level). The aim of the amendments was to determine whether soil pH was a limiting factor to plant growth or invertebrate survival and reproduction. However, it should be noted that, when soil pH is raised the availability of metals decreases, therefore, it is not possible to investigate the impact of pH on plant growth separately from the impact of metals. The testing in the pH-amended soils was not used in the overall site ranking but rather to investigate uncertainties surrounding the soil pH. The testing in pH-amended soils is discussed in Section 3.14 and in Appendix GF-10.

As mentioned beforehand, a historically limed and re-greened site (CON-07) was selected adjacent to one of the test sites (CON-08). All of the above outlined toxicity tests were conducted on the CON-07 soil so that the role of historic liming could be evaluated. The results of those toxicity tests are presented in Section 3.14.

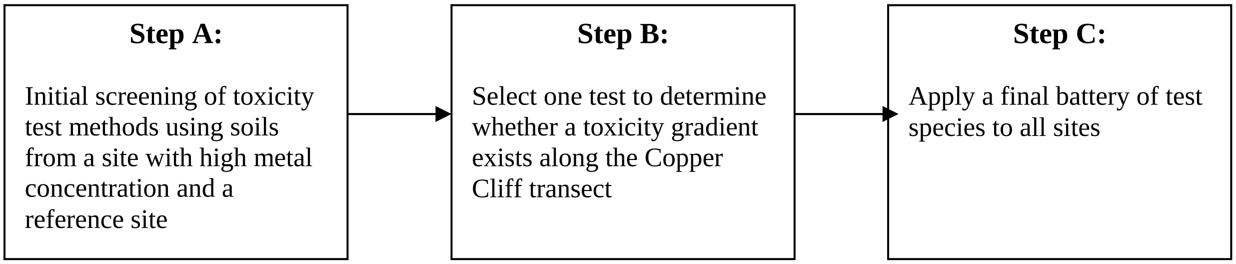
A battery approach to toxicity testing was used because the predictive value increases with the number of species types tested. A battery approach decreases the uncertainty related to the toxicity testing and several authors have suggested that the number of test species used is a critical factor in the assessment. In the case of pesticide testing, the predictive value of a test battery is known to improve with size. For instance, Blanck (1984) stated that if only three species are used, the toxicity of a chemical could be underestimated by a factor of 100 (95% confidence level) compared with the most sensitive species.

Ideally, the species used for the toxicity testing should be native to the Sudbury region and have soil toxicity test methods already developed for them. Unfortunately, to date, the vast majority of standardized Canadian toxicity tests are for species of agricultural importance rather than native species. For this study it was deemed important that the test species be representative of ecologically relevant native species or groups because it has not been demonstrated that crop species serve as surrogates for non-crop species found in nature.

The test species used for the Sudbury toxicity testing were selected by considering the following factors:

- The sensitivity of the species to metals and pH (ideally, the most sensitive species which could reside in the Sudbury area in terms of geographic considerations should be used);
- The availability of the seeds or culture animals;
- The species should be representative of native species found in Sudbury ecosystems;
- The species should be easy to maintain and culture under laboratory conditions; and
- Ideally, established toxicity test protocols should exist.

The overall approach to the toxicity testing is shown schematically as:

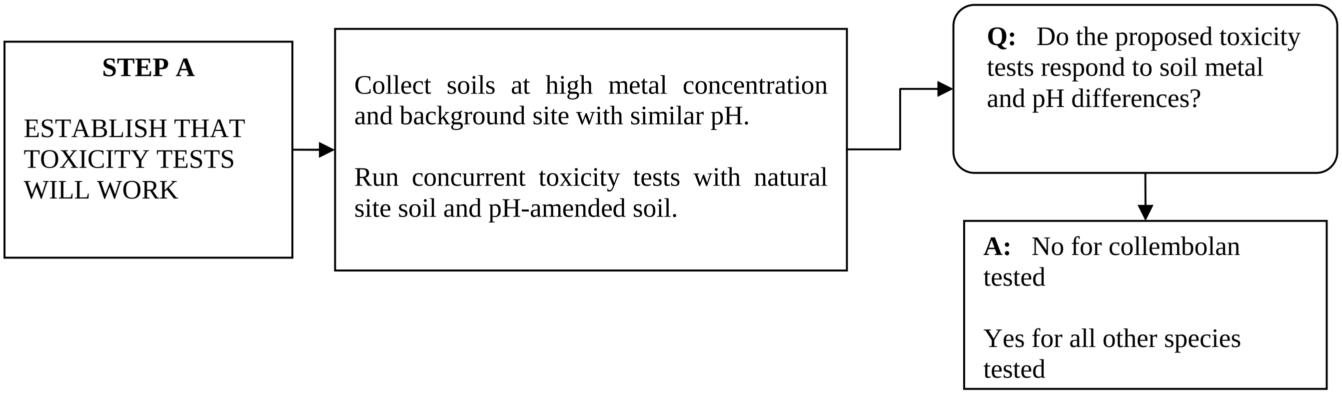


3.7.2 Methods and Results

In the following section an overview of the methods used to complete each phase of the toxicity testing is presented. The results for each phase determined the approach used for the next phase, so it is necessary to present these in a stepwise manner. As a result, in the following section, both the methods and the results for each of the three phases are presented. Further details on the methodology and results are presented in Appendix GF.

3.7.2.1 Step A: Initial Screening

The objectives of Step A were to establish that the proposed toxicity tests could be viably performed in Sudbury soil and to determine whether the observed effects could be attributed to soil metal or pH level. A schematic outlining the approach and the outcome is shown in Figure 3-22.



STEP A

ESTABLISH THAT TOXICITY TESTS WILL WORK

Collect soils at high metal concentration and background site with similar pH.

Run concurrent toxicity tests with natural site soil and pH-amended soil.

Q: Do the proposed toxicity tests respond to soil metal and pH differences?

A: No for collembolan tested

Yes for all other species tested

Figure 3-22 Summary of Approach and Outcome for Step A of the Toxicity Testing LOE

A site with high metal concentrations (as determined by Cu and Ni), and a site with low metal concentrations with comparable pH levels were selected for the Step A testing. The high metal site selected was CC-03 (Cu 948 mg/kg and Ni 1100mg/kg nitric acid digestion in core samples) and the low metal was a reference site (REF-02: Cu 41 mg/kg and Ni 32 mg/kg nitric acid digestion in core samples). A total of six plants species representing the range of species inhabiting the sites, and two invertebrates, a soft-bodied soil-dwelling species and an arthropod, were tested. The species tested were as follows:

- Trembling aspen (*Populus tremuloides*)
- Black spruce (*Picea mariana*)
- White spruce (*Picea glauca*)
- Northern wheatgrass (*Elymus lanceolatus*)
- Goldenrod (*Solidago canadensis*)
- Red clover (*Trifolium pratense*)
- Springtail (*Folsomi candida*)
- Earthworm (*Eisenia andrei*)

Various endpoints were measured in all species tested. For the plant species, the endpoints measured were shoot length, shoot mass, root length and root mass. For the invertebrates, survival, growth and reproductive success were determined.

Homogenized soil samples were used in the toxicity tests. All of the tests were conducted twice, first using natural soil from the site and again using the same soil with the pH amended to 5.2 ±0.2 ($CaCl_2$ method). An internal control soil (artificial soil) was used with each test run so that the viability of the organisms was assessed. In most cases for all species, the organisms grew well in the artificial soil, indicating that the seeds, invertebrates and test conditions were acceptable.

A summary of the results of Step A for all species can be found in Appendix GF-1, and the reports detailing the methods and results of this testing can be found in Appendix GF-2. Based on these reports, the SARA Group produced an internal document detailing the current status, results to date and proposed plan forward. A meeting was held with various members of the Technical Committee (TC) and additional staff from the MOE to achieve consensus on the proposed plan forward. All documents pertaining to the proposed plan forward can be found in Appendix GF-3.

A brief summary of the results of Step A, and the recommendations moving forward into Step B are provided as follows:

1. Trees: All three species grew in the soil collected from test sites. Differences in growth parameters were observed between the reference sites and the site with elevated metal levels. The two conifers grew equally well in the reference and the artificial soil, while the aspen seedlings were smaller in the reference soil. The aspens appeared to be most affected by the low pH of the soil. The recommendation was made to use white spruce in the test battery as a representative tree species for the Sudbury area.

2. Monocot: Northern wheatgrass was the only monocot available that had an established testing method and was an indigenous grass species. The results of the toxicity testing indicated that it was sensitive to metals and to low pH. The recommendation was made to use northern wheatgrass in the test battery as a representative monocot.

3. Dicot: Two dicots, red clover and goldenrod, were tested. Goldenrod is a herbaceous species that naturally occurs in the Sudbury area and is indicative of the boreal forest community. The Testing showed that it was very sensitive to pH (no emergence) and metals. Once the pH was raised, it was able to grow in both soils and showed effects from the metal levels in the soil. Although red clover is not a native species, it was used in the re-greening program, and is indicative of sites that have been limed and regreened. The recommendation was made to use both species in the test battery.

4. Invertebrates: Reproduction of two invertebrate species was tested (the earthworm and the springtail). The earthworm reproduction results were variable but indicated high sensitivity to both pH and metals. The springtails were insensitive to both metals and pH; therefore, this species was removed from the test battery because effects could not be detected. The earthworm avoidance test was also conducted and the results indicated that the worms avoided soils with low pH.

The recommendation was made to conduct the earthworm reproduction test at selected sites where Step B testing indicated the lowest levels of toxicity.

3.7.2.2 Step B: Toxicity Gradient

The objective of Step B was to determine whether a toxicity gradient was present along the three transects by using a rapid screening toxicity test to identify where toxicity was expected. The earthworm avoidance test was chosen to be conducted on all site soils not tested in Step A. The rationale for this screening was to reduce the number of sites required for more detailed testing using the longer earthworm reproduction test. Because the Step A testing indicated that pH was important to the toxicity of the site soils for earthworms, it was recommended that the test should be conducted on the pH-amended soils only.

The earthworm avoidance test was undertaken on the pH-amended soil from sites along the Copper Cliff transect. The earthworms avoided all the pH-amended test site soil in preference to the pH-amended reference soil. Because a toxicity gradient could not be established using this rapid screening approach, the decision was made to conduct the earthworm reproduction test on pH-amended site soil at the majority of the test sites.

The results of the earthworm avoidance test are available in Appendix GF-5. The rationale for the decisions that were made concerning the test battery is documented in the Environment Canada laboratory report, which can be found in Appendix GF-5.

3.7.2.3 Step C: Final Test Battery

Following the results of Step A and Step B, the recommended test battery included the five test species, measurement endpoints and experimental conditions outlined in Table 3.26. Toxicity tests were conducted for these species at all sites in natural site soil. In addition, tests for northern wheatgrass, red clover and earthworms were conducted concurrently in pH-amended soils.

Environment Canada Biological Methods Division (EC-BMD) completed testing of northern wheatgrass and red clover for the Copper Cliff soil, and earthworms and springtails (for all sites), while Stantec Consulting completed the testing for northern wheatgrass and red clover for the Coniston and Falconbridge transects. The Saskatchewan Research Council (SRC) completed testing of trembling aspen, goldenrod, white spruce and black spruce (for all sites).

Table 3.26 Summary of Test Species and Endpoints Used for the Toxicity Testing LOE

Ecological Component	Test Species	Endpoint	Test Conditions
Trees	White Spruce	Root Length	Natural site soil
		Root Mass	
		Shoot Length	
		Shoot Mass	
Herbaceous (Monocot)	Northern Wheatgrass	Root Length	Natural site soil and pH-amended site soil
		Root Mass	
		Shoot Length	
		Shoot Mass	
Herbaceous (Dicot)	Red Clover	Root Length	Natural site soil and pH-amended site soil
		Root Mass	
		Shoot Length	
		Shoot Mass	
Herbaceous (Dicot)	Goldenrod	Root Length	Natural site soil
		Root Mass	
		Shoot Length	
		Shoot Mass	
Invertebrate*	Earthworm*	Survival*	pH-amended site soil and natural site soil
		# juveniles*	
		Mass of juveniles*	
		Growth*	

*Invertebrate tests were not used in the overall ranking of the toxicity test LOE

The toxicity tests generated a significant amount of data from the five test species, 20 end points, 22 sites plus natural and pH-amended soils. The results of the testing for Step C are provided in Appendix GF-6. The EC-BMD, Saskatchewan Research Council (SRC) and Stantec reports detailing the methods and results of this testing can be found in Appendix GF-7. These results were used to formulate an overall toxicity testing LOE ranking for each site.

It should be noted here that ultimately the earthworm reproductive test results were not used in site ranking or the toxicity test line of evidence. The reason for not using these test results is that although adult earthworm survival was good in all test soils, there was no production of progeny in any natural, not pH-amended, soils from any of the three transects. There was production of progeny in pH- amended soils but there was no difference between sites that could be attributed to metal concentrations. Therefore, the earthworm tests demonstrated that the worms were very sensitive to soil pH, but the results did not yield information that could be used to differentiate, or rank, the test sites.

3.8 Toxicity Testing LOE (Step 1)

The objective of the toxicity testing LOE was to determine if the performance of test species in soils collected from the test sites was inhibited relative to the reference sites. Each site was given a ranking for the toxicity testing LOE. Only the results from Step C, the final battery, for natural site soils were used in the ranking. The performance of the test species was assessed independently of the metal concentration of the site soil.

Large quantities of data were evaluated to determine an overall rank for each test site. The “Toxicity Testing LOE Ranking Report,” which describes the approach taken to analyze and assess the toxicity test results to reach an overall toxicity ranking for each site, is presented in Appendix GF-9. A brief overview of the approach and a summary of the resulting ranks are presented in the following sections.

3.8.1 Ranking Approach

The first step in the ranking approach was to determine whether the test species grew and performed adequately in soil from the reference sites. To achieve this, the toxicity data at the reference sites were evaluated in a number of ways and compared to internal laboratory controls. These comparisons established that the performance of the test species in the reference soils could be considered a good comparison for the test site soils. Next, the performance of the test organisms in the test site soils was compared to their performance in the reference site soils and the test sites were classified into one of three ranks:

Rank		**Description**
Green	Low to not impacted in comparison to the reference sites	The majority of the test species at these sites performed the same or better than the test species at the reference sites.
Yellow	Moderately impacted in comparison to the reference sites	The majority of the test species at these sites performed at a level that was slightly lower than that observed at the reference sites. Some component of the soil appeared not to promote the measured endpoints (growth or reproduction) of the test species.
Red	Severely impacted in comparison to the reference sites	The majority of the test species at these sites performed at a level that was much lower than that observed at the reference sites. Some component of the soil appeared to seriously impact the measured endpoints (growth or reproduction) of the test species.

Unlike the other LOE, two separate approaches were used to independently rank the test sites:

- A comparison of the test site results to each reference site; and
- A comparison of test site results to a mean of all three reference sites.

The results from each approach were compared. Where the two approaches produced identical results, this became the overall rank for the test site, but where the two approaches produced different results, the site was given a split ranking.

The methods used in the two approaches are outlined in the following sections.

Approach 1: Compare measured toxicity test endpoints from the test site soil to each of the three individual reference sites.

The toxicity data from each of the test sites were statistically compared to the results from each of the three reference soils (REF-02, REF-03 and REF-04) using an analysis of variance (ANOVA) to determine if there was a significant ($p < 0.05$) difference among treatment means. Using the results of an ANOVA analysis, the toxicity test results from each site were ranked by endpoint, then by species to eventually produce a site rank for Approach 1.

Approach 2: Compare measured toxicity test endpoints from the test site soil to the REF_{mean}.

The toxicity results from each of the test sites were compared to the mean of the toxicity endpoint from the three reference soils, referred to as REF_{mean}. The data values from REF_{mean} and each test site were compared by calculating the percent difference. The comparison of the test sites to REF_{mean} was ranked by endpoint, then by species to eventually produce a site rank for Approach 2. The REF_{mean} approach was used to eliminate some of the variability observed for some endpoints and some test species between reference sites.

The two approaches were combined to give the overall ranking for the site. This process is summarized in Figure 3-23 and is described in more detail below.

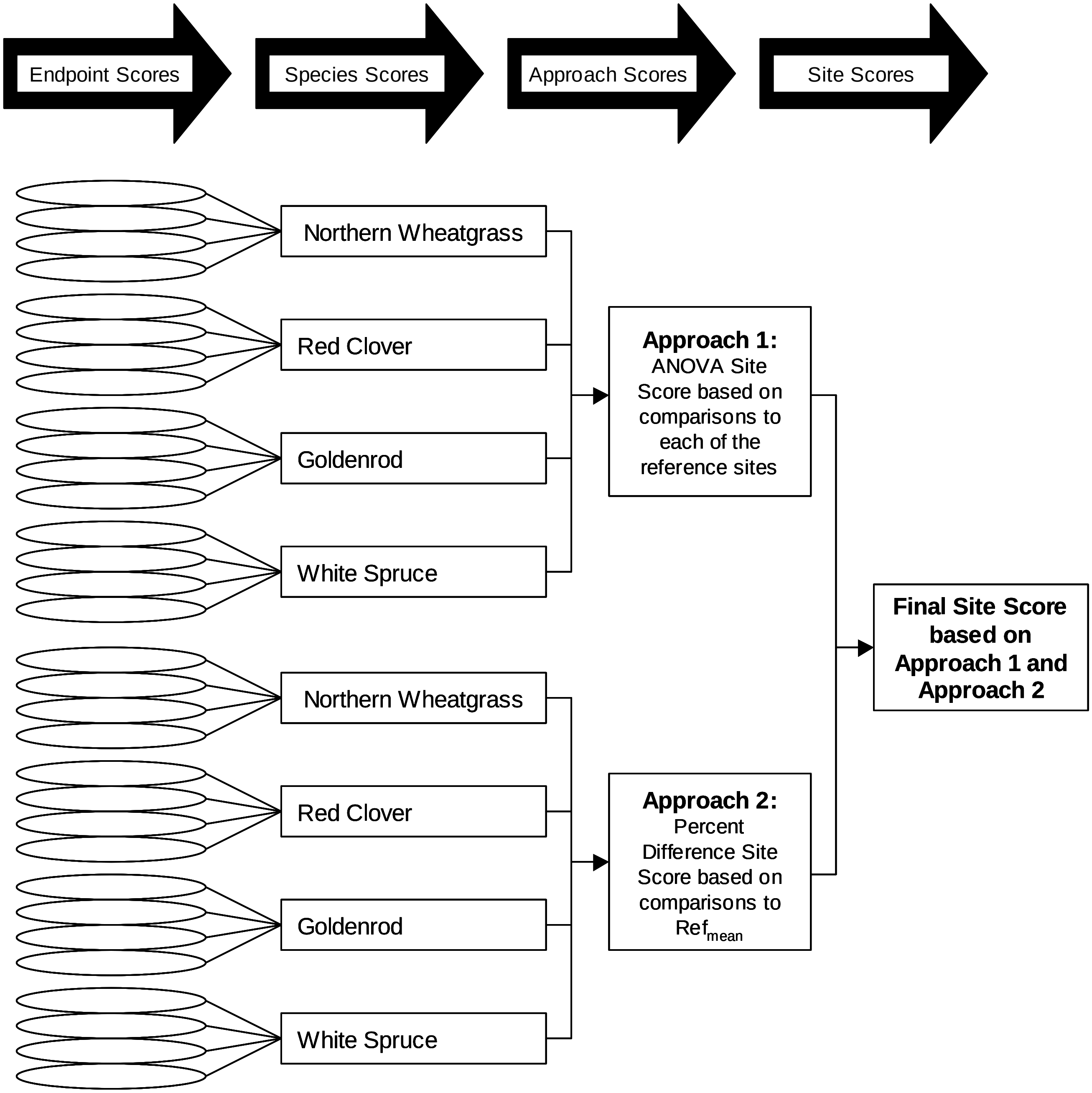


Figure 3-23 Overall Site Ranking Approach for Soil Toxicity Data for the Toxicity Testing LOE

3.8.2 Reference Site Evaluation

Most of the standard toxicity test species and protocols were developed for agricultural soils, not for soils from northeastern Ontario boreal forests. The Sudbury soils differ markedly from agricultural soils in that they display low soil pH and low mineral and nutrient content. Therefore, various procedures (described in more detail in the ranking report in Appendix GF-9) were undertaken to verify the performance of the toxicity tests in the reference soils. These evaluations included an evaluation of the performance of the organisms in artificial soil to provide baseline measurements; an evaluation of the sensitivity of the organisms to pH in artificial soil; and a comparison of the performance of the organisms in the reference soils to the artificial soil with a comparable pH. These evaluations established that the soil from the reference sites provided an adequate baseline for comparison to the test site soils.

The results also demonstrated that in the absence of pH as an influencing factor, performance of the test species in the reference soils were sometimes limited by other variables. This finding did not affect the usefulness of the reference soils as a comparison to the test soils but did demonstrate that the chosen test species did not always perform well in Sudbury soils. In the absence of more regionally appropriate test species developed for forested regions, the battery of species selected for this study was considered to be the most appropriate option available at the time.

Although there was variation between the performances of the test species in the soil from the three reference sites, no one reference site stood out as particularly poor; some reference sites were excellent for one species but not for another. For comparative purposes, a mean of the values for each endpoint for the three reference sites was established and was referred to as REF_{mean}. The REF_{mean} value provided a baseline for comparison with the test sites and was considered indicative of the average performance of the test species in soil from forested regions of the Sudbury area.

3.8.3 Test Site Evaluation

The approach and results of the evaluation that produced an overall ranking for each test site for the toxicity testing LOE are presented in this section. An overall ranking (severely impacted (red), moderately impacted (yellow), or low to not impacted (green)), was determined for each site based on the results of the toxicity tests in natural site soil using the two separate approaches described above.

Table 3.27 provides a set of logic rules showing how the results from each endpoint or species were evaluated to produce a ranking for the next level (*i.e.* endpoints to rank species, species to rank site). An overall rank is provided for every possible combination of rankings for a set of four parameters. The same logic was utilized for the determination of the endpoint ranking (where, for instance, root length, shoot length, root weight and shoot weight would be parameters 1, 2, 3 and 4) and the test species ranking (where, for instance, northern wheatgrass, red clover, white spruce and goldenrod would be parameters 1, 2, 3 and 4).

An overall rank of green represents a performance similar to or better than the reference sites, yellow represents a performance slightly lower than the reference sites and red represents a performance much lower than the reference sites.

Table 3.27 Sample Ranking Table and Possible Outcomes for the Overall Performance of Test Species for the Toxicity Testing LOE

Parameter 1[a]	Parameter 2	Parameter 3	Parameter 4	Overall Rank	Overall Performance
[b]Green	Green	Green	Green	**Green**	Performance is similar to or better than reference sites
Green	Green	Green	Yellow	**Green**	
Green	Green	Yellow	Yellow	**Yellow**	Performance is slightly lower than reference sites
Green	Yellow	Yellow	Yellow	**Yellow**	
Yellow	Yellow	Yellow	Yellow	**Yellow**	
Yellow	Yellow	Yellow	Red	**Yellow**	
Red	Green	Green	Green	**Yellow**	
Green	Green	Yellow	Red	**Yellow**	
Green	Yellow	Yellow	Red	**Yellow**	
Yellow	Yellow	Red	Red	**Red**	Performance is much lower than reference sites
Yellow	Red	Red	Red	**Red**	
Red	Red	Red	Red	**Red**	
Red	Red	Red	Green	**Red**	
Red	Red	Green	Green	**Red**	
Green	Yellow	Red	Red	**Red**	

[a] where "parameter" represents individual endpoint for endpoint ranking, species for species ranking, approach for approach ranking
[b] where each row represents a species, a site…

For example, if applied to endpoints, the ranking legend might be:

Test Species: Northern Wheatgrass (NWG)

Shoot Weight	Shoot Length	Root Length	Root Weight	Overall Rank
The shoot weight is between 20 and 50% lower than REF_{mean}/reference sites	The shoot length is between 20 and 50% lower than REF_{mean}/reference sites	The root length is more than 50% less than REF_{mean}/reference sites	The root weight is more than 50% less than REF_{mean}/reference sites	At this site NWG can be considered severely impacted with respect to the performance of NWG at the reference sites. The roots of this species are more affected than the shoots

If applied to test species, the ranking legend might look like this:

Northern Wheatgrass	Red Clover	White Spruce	Goldenrod	Overall Rank
Severely Impacted	Low to No Impact	Moderately Impacted	Severely Impacted	Two species are severely impacted (NWG and goldenrod), one is moderately impacted (white spruce) and one does not appear to be impacted (red clover) in comparison to the reference sites/REF_{mean}. Overall, this site is ranked severely impacted.

3.8.3.1 Overall Site Ranking

The two approaches were weighted equally in the overall ranking for each test site (Table 3.28). If the approaches provided identical rankings, then no further evaluation was required. If the two methods were not in agreement, the site was given a split ranking (such as red/yellow or yellow/green) to illustrate the separate rankings.

Copper Cliff: Five of the seven test sites were ranked “severely impacted” by approach #1, and six of seven were ranked “severely impacted” by the second approach.

Coniston: The sites on the Coniston transect were ranked either “severely impacted”, or between “severely impacted” and “moderately impacted.” The exception to this was site CON-01, which was ranked “moderately impacted” by both ranking methods.

Falconbridge: Site FB-01, was ranked “severely impacted.” FB-02 and FB03 were given a split rank between “severely impacted” and “moderately impacted”. The remaining two sites were given “low to moderately impacted” ranks.

In addition to the toxicity testing in natural site soil, toxicity testing was also conducted in soil that had been amended to raise the pH to approximately 5.2 (see Appendix GF-10 for detail on the toxicity testing in pH-amended soil).

Raising the pH of the soil often reduced the toxicity of the soil, but did not alleviate it altogether. The results are broadly consistent with a hypothesis that adverse impacts to terrestrial biota are related to the available fraction of metals in the soil. However, this interaction is potentially complicated by the relative presence of multiple contaminants and other important soil characteristics. The results of the toxicity tests in pH-amended soil were not incorporated into the site rankings, but they do contribute some information on the impact of low pH on the performance of the test organisms. Further evaluations of the changes in performance of plants in pH amended soil and in comparison to historically limed sites are provided in Section 3.14.

Table 3.28 Summary of Site Ranking for the Toxicity Testing LOE in Natural Soil

Site	Rank	
	Approach 1	Approach 2
CC-01	Red	Red
CC-02	Red	Red
CC-03	Red	Red
CC-04	Red	Red
CC-06	Yellow	Red
CC-07	Red	Red
CC-08	Yellow	Yellow
CON-01	Yellow	Yellow
CON-02	Red	Red
CON-03	Yellow	Red
CON-05	Yellow	Red
CON-06	Red	Red
CON-08	Red	Red
FB-01	Red	Red
FB-02	Yellow	Red
FB-03	Yellow	Red
FB-05	Green	Yellow
FB-06	Green	Green

3.9 Decomposition Assessment: Methods and Results

The process of litter decomposition is critical for maintaining site fertility and productivity. Through the decomposition of litter, nutrients return to the soil where they again become available to the plant ecosystem. A decay rate that is too slow or too fast can have negative effects, such as nutrient losses or poor growth conditions (Andersson, 2005). Elevated concentrations of some metals, such as copper and nickel, in soil have been linked with reduced rates of litter decomposition and an increase in the litter layer on forest floors (Andersson, 2005). Heavy metals in soils are known to have a deleterious effect on soil microbial activity.

Decomposition was recognized as a vital function in the forest system and as such was included as an LOE in the evaluation of Objective #1. To achieve this, a year-long *in situ* litter bag study was initiated. The objective of this study was to measure the mass loss of leaf litter, as well as the concentration of heavy metals and macronutrients, in *in situ* litter bags containing white birch (*Betula papyrifera*) leaves over a 13 month period at the test and reference sites. This study was undertaken by the SARA Group in partnership with researchers at MIRARCO/Laurentian University. The following section describes the methods and results of the litter bag study.

3.9.1 Methods

The methods used to construct, place and analyze the litter bags are presented in Appendix GB Protocol 9 and are discussed in a report prepared by MIRARCO for the SARA Group in Appendix GG4-1b. These methods were written by the SARA Group and were based on the work of Johnson and Hale. (2004) and the European Guidance Document: *Effects of Plant Protection Products on Functional Endpoints in Soil (EPFES)*, Lisboa, 2002. The EPFES guidance document describes a litter bag approach used for bags buried in agricultural settings. These basic methods were adjusted using the findings from Johnson and Hale (2004) to design a decomposition study appropriate to a forested region in northeastern Ontario. Birch leaves were used instead of straw, the bags were left on the forest surface instead of being buried and the duration of the study was a full year.

Figure 3-24 Preparation of litter bags for decomposition assessment: a) preparation of white birch leaves; b) weighing birch leaves; c) birch leaves in nylon mesh litter bags; and, d) litter bags on forest surface.

The litter material used was white birch foliage collected from one site (Zone 17 495795 E, 5137908 N) in the fall of 2004 from five individual trees within a 10 m radius. The location of this site is marked on Figure GG4-2-1 in Appendix GG4. Approximately 10 g (fresh weight) of leaf litter was placed separately into nylon mesh bags (Figure 3-24). The bags were placed at the sites in October 2004 with the last bags retrieved in November 2005. At each site, 25 litter bags were placed on the forest floor in a 5 x 5 block design, with additional bags at the reference sites (Figure 3-25). Five bags from each site were collected at 7, 8, 9, 10, and 13 months, respectively, from the initial time of placement in October, 2004. Litter bags were placed at a total of 20 sites: this included 3 reference sites, 1 limed site (CON-07) and 16 test sites. Two of the test sites, CC-03 and CON-05, were located on company (Vale Inco, Xstrata Nickel) property in areas where the access was restricted due to safety concerns. As a result of the complexities of co-ordinating site entry on a regular basis litter decomposition tests were not conducted at these two sites. The limed site was included for comparative purposes but was not considered in the final site ranking.

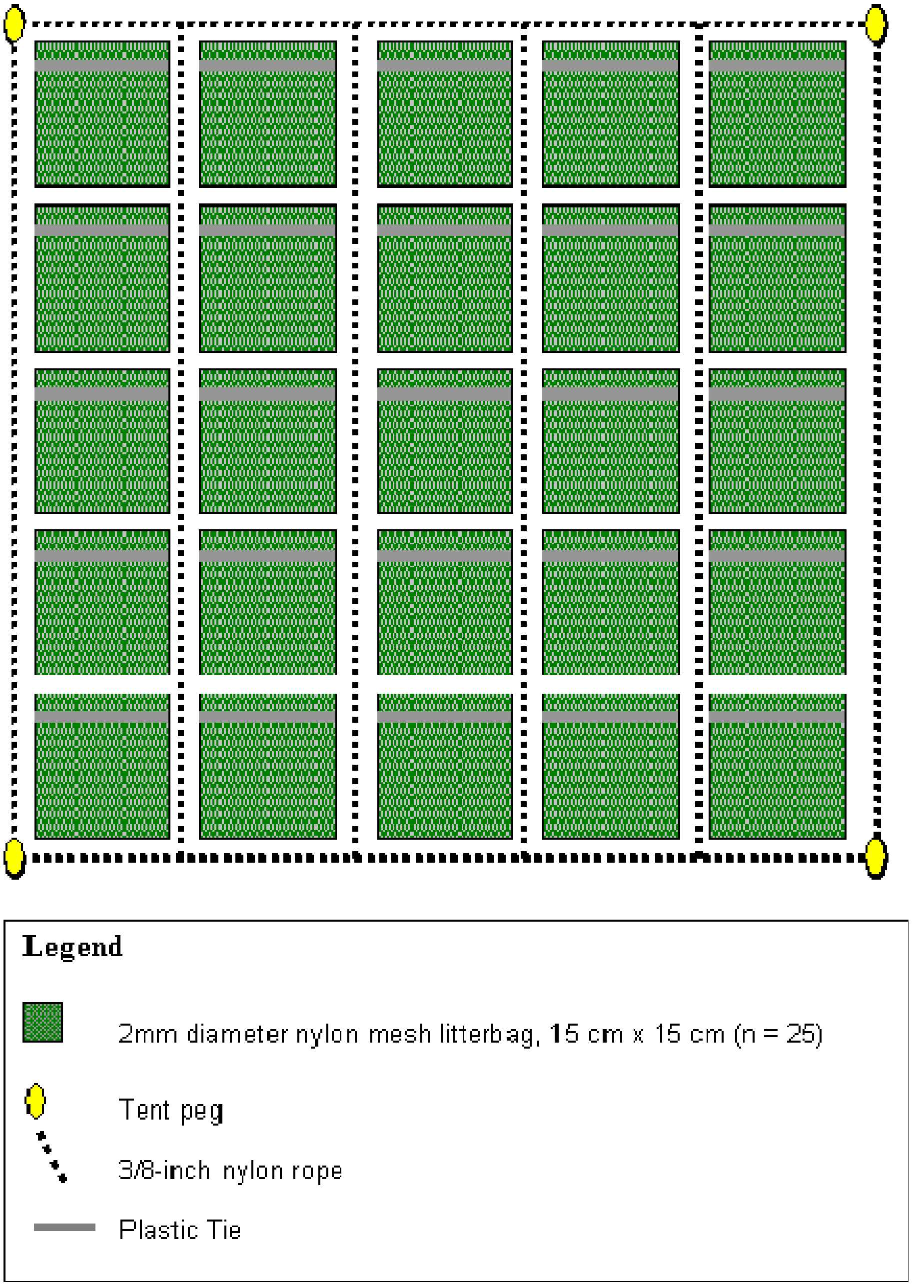


Figure 3-25 Schematic Diagram of the Litter bag Layout for the Decomposition LOE

A predetermined “reference criterion” was developed using the guidelines set out in EPFES prior to initiating the test. This criterion was the level of decomposition (percent mass loss) that was to occur at the reference sites in a particular time period for that site to be considered to have a decomposition rate typical of a forested site in northeastern Ontario. Based on the EPFES guidelines and the study conducted by Johnson and Hale (2004), it was decided that the mass loss at each reference site should be at least 50%. The rationale of the 50% criterion is discussed further in Appendix GG4.

Because decomposition was estimated as the loss of dry mass over time, initial dry masses of leaves in the litter bags had to be measured. This was achieved using a fresh weight to dry weight conversion factor determined at the start of the experiment. Conversion factors were calculated as the average dry mass of five 10 g fresh weight samples dried at 80°C for 72 hours (Appendix GG2).

Debris and plant material were removed from the exterior of the litter bags and the contents were washed to remove surface deposition, prior to drying. This washing procedure was kept as gentle as possible to minimize the amount of leaching or abrasion. The methods used for this analysis are detailed in Appendix GG1-b. The mass loss at each site was calculated as the difference between the initial dry weight of the leaves (estimated from fresh weight using the conversion factor calculated at the start of the study) and the end dry weight of the decomposed leaves.

3.9.2 Results

The following section provides an overview of the results with the detailed data from the litter bag study presented in Appendix GG1. This report includes an interpretation of the litter bag results that differs from the ranking approach used by the SARA Group. The ranking used by the SARA Group is presented in Appendix GG-4. A brief summary of the results is presented in the following sections.

3.9.2.1 Reference Sites

The mean mass loss after 13 months at each of the reference sites is presented in Table 3.29. The values represent the mean percent loss of replicate samples at each site. There was variability in mass loss among the reference sites. The final mass loss at REF-02, REF-03 and REF-04 was 57%, 73% and 51%, respectively. The accumulated mass loss at REF-03 exceeded the mass loss at REF-02 and REF-04 by 16% and 22%, respectively. The final mass loss for REF_{mean} (average of the three sites) was 60%.

Table 3.29 Final Mass Loss for Litter bags after 13 Months at the Reference Sites

Site	Final Mass Loss (%)
REF-02	57
REF-03	73
REF-04	51
REF_{mean}	60

3.9.2.2 Test Sites

The detailed results of the mass loss at the test sites are presented in Appendix GG1 a and b, and in the ranking report in Appendix GG4. The mean final mass loss at each of the test sites ranged from 35 to 58% and is presented in Table 3.30.

Table 3.30 Final Mass Loss for Litter bags after 13 Months at the Test Sites

Site	Final Mass Loss (%)
FB-01	38
FB-02	50
FB-03	52
FB-05	43
FB-06	50
CON-01	50
CON-02	35
CON-03	48
CON-06	46
CON-07*	53
CON-08	35
CC-01	51
CC-02	45
CC-04	58
CC-06	44
CC-07	43
CC-08	48

*CON-07 is the historically limed and re-greened site

3.10 Decomposition LOE (Step 1)

The objective of the decomposition LOE was to determine whether decomposition at the test sites was different from that of the reference sites. The following sections summarize the approach, methods and results of the ranking of the decomposition LOE. The detailed "Decomposition Assessment LOE Ranking Report" is available in Appendix GG4.

3.10.1 Approach

The overall approach used to evaluate and rank the decomposition LOE at the test sites is shown in Figure 3-26 and can be summarized as follows:

- Place litter bags at sites, collect a subset from the reference sites at intervals after placement and calculate mass loss.
- Use mass loss to evaluate decomposition at reference sites.
- Use mass loss to determine decomposition rate constants (*k*=slope of regression line) for each site.
- Compare *k*-values from each test site against the *k*-value of the mean of the reference sites to assign test site ranks.

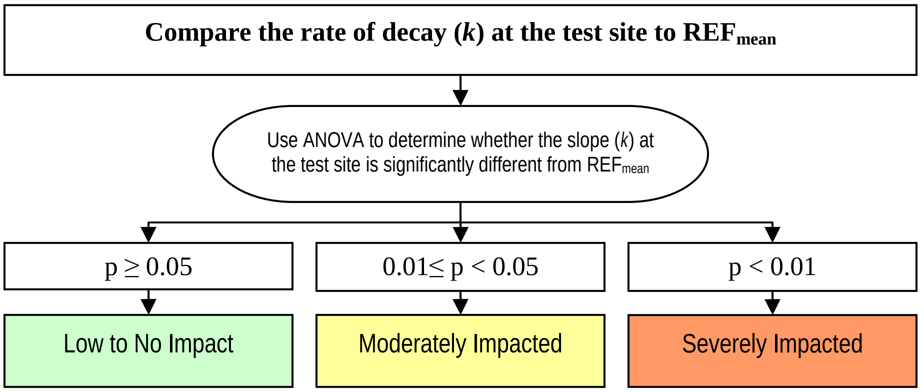


Figure 3-26 Summary of the Overall Ranking Approach for the Decomposition LOE using ANOVA

The decomposition results at each test site were compared to the mean of the reference sites (REF_{mean}) to determine whether the ability of microorganisms to decompose matter was affected. The test site ranks provide an indication of the ability of the microbial communities at each site to decompose organic matter. The three rank categories were as follows:

Rank		**Description**
Green	Low to not impacted in comparison to the reference site mean	There was no difference between the rate of decomposition or the amount of mass loss at the test site when compared to the mean of the reference sites.
Yellow	Moderately impacted in comparison to the reference site mean	The rate of decomposition or mass loss was impacted in comparison to the mean of the reference sites.
Red	Severely impacted in comparison to the reference site mean	The rate of decomposition or mass loss was severely impacted in comparison to the mean of the reference sites.

This ranking was achieved by comparing the rate of decay, represented by the regression slope (*k*-values), between test sites and REF_{mean} *k*-values.

ANOVA was used to establish the rank at each test site, which depended upon the significance level of the difference between the test site and REF_{mean}. The complete rationale for the ranking of the test sites is located in the Decomposition LOE ranking report in Appendix GG-4.

3.10.2 Reference Site Evaluation

The results obtained from the three reference sites were evaluated to determine the following:

- Whether the amount of decomposition, as determined by mass loss at the reference sites, was adequate (*i.e.*, typical of what could be expected in the Sudbury ecosystem); and
- Whether the degree of variability between the reference sites was acceptable.

Few studies have been conducted to date using foliar litter bags placed on surface soils in forested areas in Canada. The only directly comparable literature is the work of Johnson and Hale (2004), which was conducted in the Sudbury region, using a very similar approach. In their study, the maximum mass loss of organic matter in 12 months was just over 50% and no further increase in mass loss occurred between months 12 and 18. The EPFES guidance document recommends that litter bag tests (with bags buried in agricultural soil) continue until 60% decomposition occurs in the bags laid at the reference sites, or if this is not attained, then the test should continue for one year. Given the limited data available in the literature the SARA Group relied on guidance from EPFES and Johnson and Hale (2004). The SARA Group established the duration time and minimum percent decomposition for the Sudbury ERA decomposition study to be one year or 50% decomposition at the reference sites. The amount of decomposition at the three reference sites (51 to 73%) was considered acceptable for forested regions in Ontario. The mass loss at all three reference sites met the validity criterion.

Although the mass loss at the three reference sites was considered adequate, there was considerable variability between sites. The reference sites each had different forested communities and soil types, which could alter decomposition rates at the site. Due to the experimental nature of the litter bag study (that is, no standard test methods currently exist for this test in forested communities), the variation between these sites was considered to be indicative of the natural variation that exists in decomposition within forested areas in northeastern Ontario (Appendix GG-4). A mean of the mass loss of white birch leaf litter between the three reference sites results was calculated and referred to as REF_{mean}. The final mass loss for REF_{mean} (average of the three sites) was 60%. The REF_{mean} was used as the basis for subsequent comparisons of litter decomposition at each test site.

3.10.3 Test Site Evaluation

The test sites were compared to REF_{mean} and a final ranking was obtained based on the established ranking approach. Table 3.31 provides the overall ranking for each site for the decomposition LOE. With the exception of two sites, CC-04 and FB-05 (low impact), decomposition at all of the test sites evaluated was ranked either moderately or severely impacted when compared to the decomposition at the reference sites.

Table 3.31 Summary of the Overall Site Ranking for the Decomposition LOE

Site	Rank
CC-01	Red
CC-02	Red
CC-03	N/A
CC-04	Green
CC-06	Red
CC-07	Red
CC-08	Yellow
CON-01	Red
CON-02	Red
CON-03	Red
CON-05	N/A
CON-06	Red
CON-08	Red
FB-01	Red
FB-02	Red
FB-03	Yellow
FB-05	Green
FB-06	Red

3.11 Final Site Ranking and Integration of LOE

Four different lines of evidence were used to assess Objective #1 of the Sudbury ERA. The use of multiple approaches, or lines of evidence (LOE), to assess ecosystem impairment is becoming more common as our understanding of the complex interactions between the physical, chemical and biological components of ecosystems expands. The use of multiple LOE in the assessment of ecosystem impairment minimizes the occurrence of false-positive and false-negative conclusions (Rutgers and den Besten, 2005); however, it requires that the LOE be integrated, generally with some form of weight-of-evidence (WOE) approach (Burton *et al*., 2002b). Chapman *et al*. (2002) describe a weight-of-evidence analysis as a determination of possible ecological impacts based on multiple LOE, incorporating judgements concerning the quality, extent and congruence of the data. The WOE framework should be logical, transparent, readily understandable by lay personnel and should appropriately distinguish between hazard and risk.

WOE frameworks are available in the literature, although these are more common for sediments (*e.g.*, sediment quality triad) and aquatic systems than for terrestrial systems (Rutgers and den Besten, 2005). A recent issue of the journal "Human and Ecological Risk Assessment" presented a series of 10 papers on the WOE approach, including: Burton *et al*. (2002a and b), Batley *et al*. (2002), Chapman *et al*. (2002), Reynoldson *et al*. (2002a and b) and Smith *et al*. (2002). Chapman *et al*. (2002) described the five general categories of WOE frameworks: indices, statistical summarization, scoring systems, logic systems, and best professional judgement.

For indices, the data from each LOE are normalized and combined; although Chapman *et al*. (2002) cautioned that the development and use of indices results in information compression that can negate full use of the WOE approach. Statistical summaries of test site data may be compared to reference data, and the distance from the reference data is scored or ranked. In scoring systems, measurement endpoints are weighted based on best professional judgement, in terms of the strength of their relationship to the assessment endpoints. Logic systems for WOE involve a series of questions or hypotheses that are tested and scored in terms of their likelihood as causative mechanisms. Best professional judgement as a WOE framework simply applies expert opinion to the available data to determine ecosystem status. Overlap between the categories, as well as combinations of frameworks are also possible. Chapman *et al*. (2002) generally recommend the use of tabular decision matrices within a logic system.

This assessment used a combination of the above framework to provide a very comprehensive, logical and transparent approach to evaluate a range of ecosystem variable and functions. The preceding sections described how each test site was ranked for each LOE. This section describes how the four LOE were integrated to provide a final ranking for each site. This completes the first of the three steps used to evaluate Objective #1 as established earlier in Section 3.2 (Figure 3-3). The approach to assigning the overall site ranks and a summary of each site is presented in the sections below.

The process of distilling down a large volume of diverse data into a relatively simple conclusion of "red," "yellow" or "green" (severely, moderately, or low to not impacted) is analogous to using a biological index. Indices have been used widely in environmental assessments, but may also be criticized because the detailed information appears to be lost when an overall "rank" is given. The SARA Group does not feel this is a deficiency in this approach because the ERA has been documented such that anyone can review the volumes of diverse data collected for each of the four LOE.   Also, extensive local expert knowledge was used to validate the ranking. The final ranking summarizes this large volume of data into results that facilitate decision-making by risk managers.   Of course, planning for risk management will also require attention to the detailed data for each site. This information is available in the appendices to this report.

3.11.1 Final Site Ranking Approach

The overall site ranking incorporated the four LOE, using the following weight-of-evidence approach:

- The plant community assessment was considered the most significant LOE, because it reflected the actual current ecological condition of the sites;
- The toxicity testing LOE was given the second most significant weighting when integrating the LOE;
- More weight was given to the results of the toxicity testing and plant community than to the other LOE because of the amount of data collected and number of variables examined. If these LOE were both ranked severely impacted, then the site was considered severely impacted;
- Soil characterization was not given as much weight in the final ranking process as either the plant community assessment or the toxicity testing LOE. However, it should be noted that the soil characterization was considered throughout the ranking processes of each of the three other LOE. Soil conditions were taken into account with respect to the plant community, decomposition and toxicity testing LOE;
- Although very ecologically significant, decomposition was weighted less than the other LOE because the litter bag study only measured one variable, and was based on a modified test protocol.

To test this approach and to ensure it would eliminate bias in the final site ranking, the table of final ranks for the four LOE was sent to 12 independent scientists and lay people. Each person was provided with background information about the LOE and was asked to give each site a final ranking. The results of this “ranking survey” helped the SARA Group develop the above rationale, which encompasses the thoughts of the various experts represented as well as those who have been intimately involved with the development of the LOE and of the ranking approach.

3.11.2 Final Site Rankings

Using the approach outlined above, the site ranking for each LOE as well as the final rank is summarized in Table 3.32. The spatial distribution of the test sites and their ranking is illustrated in Figure 3-27.

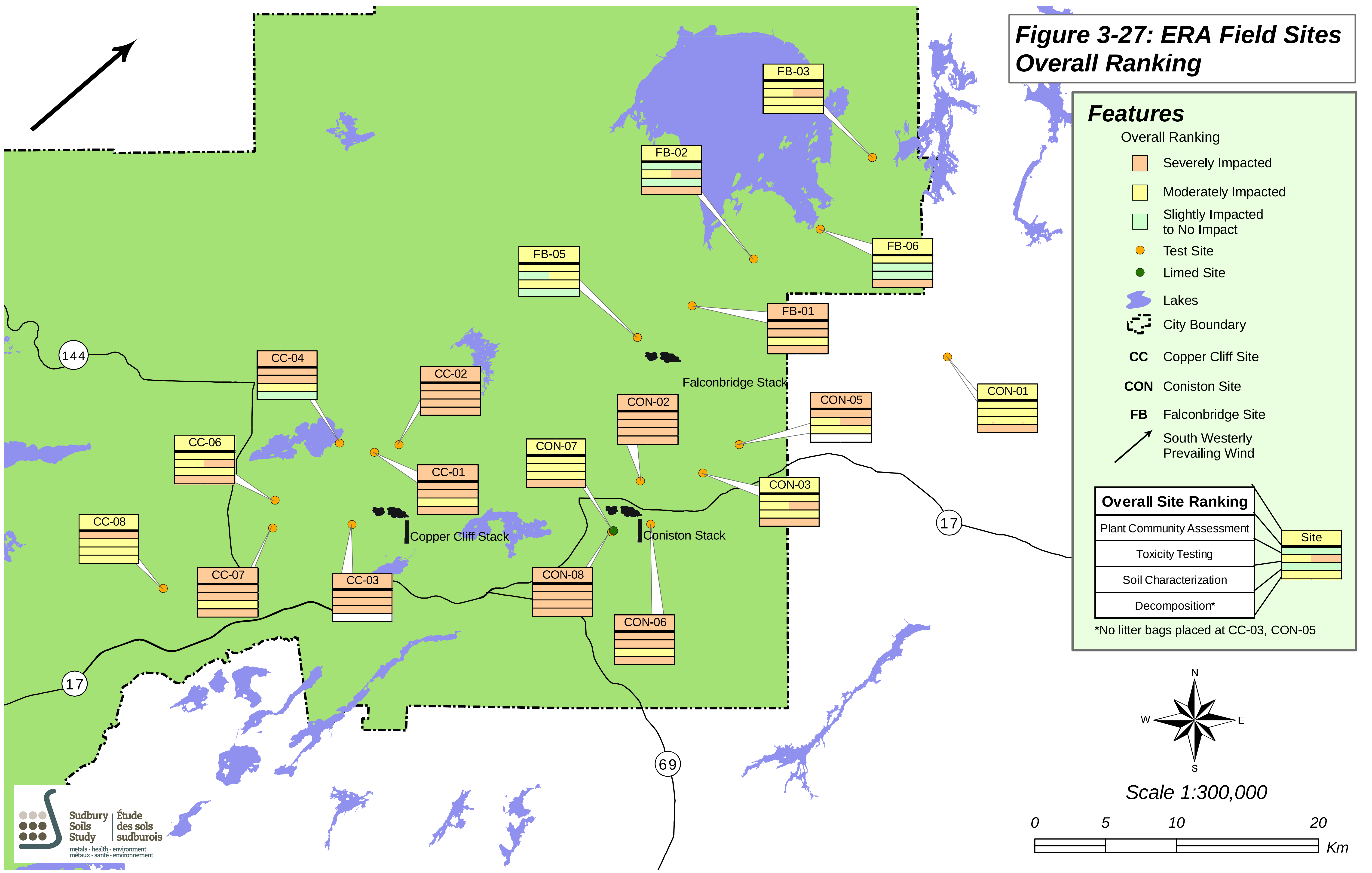
Table 3.32 Summary of the Final Site Rankings after the Integration of all LOE in Natural Soil

Site	LOE					Final Rank
	Plant Community Assessment	Toxicity Testing		Soil Characterization	Decomposition Assessment	
		Approach 1	Approach 2			
CC-01	Red	Red	Red	Yellow	Red	Red
CC-02	Red	Red	Red	Red	Red	Red
CC-03*	Red	Red	Red	Red	N/A	Red
CC-04	Red	Red	Red	Yellow	Green	Red
CC-06	Yellow	Yellow	Red	Yellow	Red	Yellow
CC-07	Red	Red	Red	Yellow	Red	Red
CC-08	Red	Yellow	Yellow	Yellow	Yellow	Yellow
CON-01	Yellow	Yellow	Yellow	Yellow	Red	Yellow
CON-02	Red	Red	Red	Red	Red	Red
CON-03	Yellow	Yellow	Red	Yellow	Red	Yellow
CON-05*	Red	Yellow	Red	Yellow	N/A	Red
CON-06	Red	Red	Red	Yellow	Red	Red
CON-08	Red	Red	Red	Red	Red	Red
FB-01	Red	Red	Red	Yellow	Red	Red
FB-02	Green	Yellow	Red	Green	Red	Yellow
FB-03	Yellow	Yellow	Red	Yellow	Yellow	Yellow
FB-05	Yellow	Green	Yellow	Yellow	Green	Yellow
FB-06	Yellow	Green	Green	Green	Red	Yellow

* CC-03 and CON-05 were located on company property (Valet Inco, Xstrata Nickel) and had restrictive access due to safety concerns. For this reason, the SARA Group was unable to assess decomposition rates at these sites.

A one-page description, including a photograph of site vegetation and landscape and a summary of the individual LOE, is provided on the following pages. These profiles are intended to provide the reader with a better understanding of the conditions at each site in a concise format.

Figure 3-27: ERA Field Sites Overall Ranking



*No litter bags placed at CC-03, CON-05

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CC-01: Ranked Severely Impacted		
Three of the four LOE were ranked severely impacted. The plant community was stressed; plants and invertebrates did not perform well in this soil during the toxicity testing; the site was eroded and the soil did not display the characteristics of a good growth medium; and, the rate of decomposition was severely impacted. Overall, this site was ranked severely impacted.		
Line of Evidence	**Rank**	**Comments**
Plant Community Assessment 	R	Three indicators were ranked severely impacted; one was ranked moderately impacted. The site displayed many characteristics of a stressed plant community. Biodiversity and ecological integrity were low. Low numbers of species and the moderate presence of bare mineral soil suggested that the site and soil conditions did not favour successful germination and establishment of a range of forest plant species. There was abundant evidence of risks to long-term site productivity. Soil and water conservation was ranked as moderate. The soils were exposed on portions of the site, and were only protected by a small amount of leaf litter. However, the terrain was relatively level, reducing the chance of surface erosion.
Toxicity Testing	R	The majority of test species did not grow well in the natural soil when compared with the reference sites. There was agreement between the two approaches.
Soil Chemical and Physical Analysis	Y	The site had eroded relict soil sub-surface horizons exposed as the growing medium. Although the organic matter content was relatively high and was similar to the reference sites, the lack of stable organic and mineral horizons affected the site fertility and suitability as a growth medium. In terms of fertility parameters, the site was poorer than the reference sites.
Litter Bag Decomposition Analysis	R	The rate of decomposition (k) was lower at CC-01 than for the REFmean and indicated a severe impact on ecosystem function. This could lead to increasingly larger differences in total decomposition over time.

CC-02: Ranked Severely Impacted

All of the LOE were ranked severely impacted. The plant community was stressed; plants and invertebrates did not perform well in this soil during the toxicity testing; the soil did not display the characteristics of a good growth medium as for CC-01. Overall, this site was ranked severely impacted.

Line of Evidence	Rank	Comments
Plant Community Assessment 	R	All four indicators were ranked severely impacted. The site displayed many characteristics of a stressed plant community. Biodiversity was very low, as was ecological integrity. The soil and site conditions did not favour successful germination or the establishment of a range of forest plant species. There was abundant evidence of risks to long-term site productivity. The site was at risk with respect to soil and water conservation partially because of the steep slopes and the presence of exposed mineral soil.
Toxicity Testing	R	The majority of test species did not grow well in the natural soil when compared to the reference sites. There was agreement between the two approaches.
Soil Chemical and Physical Analysis	R	The site was not eroded and consequently the regional mature soil at this site was Eluviated Dystric Brunisol. The coarser soil texture at this site indicated that the moisture holding capacity was reduced. The soil contained adequate organic carbon but lower total and available nitrogen, and was deficient in available Mg, K and N. Several fertility parameters were found to be deficient relative to the reference sites.
Litter Bag Decomposition Analysis	R	The rate of decomposition (k) was lower at CC-02 than REFmean and indicated a severe impact on ecosystem function. This could lead to increasingly larger differences in total decomposition over time.

CC-03: Ranked Severely Impacted

The three LOE that were evaluated were ranked severely impacted. The plant community was stressed; plants and invertebrates did not perform well in this soil during the toxicity testing; the site was eroded and the soil did not display the characteristics of a good growth medium resulting in an overall site rank of severely impacted.

Line of Evidence	Rank	Comments
Plant Community Assessment 	R	All four indicators were ranked severely impacted. The site displayed many characteristics of a stressed plant community. Biodiversity and ecological integrity were low. The low numbers of species present, the almost complete absence of tree regeneration and the large amount of bare mineral substrate suggested that the site and soil conditions did not favour successful germination or the establishment of a range of forest plant species. There was abundant evidence of risk to long-term site productivity and soil and water conservation was scored very low. With low tree density and only a small amount of leaf litter cover present, there was a high risk for erosion.
Toxicity Testing	R	The majority of test species did not grow well in the natural soil when compared to the reference sites. There was agreement between the two approaches.
Soil Chemical and Physical Analysis	R	The site was eroded with relict soil sub-surface horizons exposed as the growing medium. Although the organic matter content was relatively high, and was similar to the reference sites, the lack of stable surface organic and mineral horizons affected the site fertility and suitability as a growth medium. The site did appear to be altered relative to the reference sites in terms of fertility parameters and exchange chemistry.
Litter Bag Decomposition Analysis	-	Not evaluated

CC-04: Ranked Severely Impacted

Two of the four LOE were ranked severely impacted. The plant community was stressed; plants and invertebrates did not perform well in this soil during the toxicity testing (the soil did not display the characteristics of a good growth medium). Although the rate of decomposition was not impacted, the results of the other LOE resulted in an overall site rank of severely impacted.

Line of Evidence	**Rank**	**Comments**
Plant Community Assessment 	R	Two indicators were ranked severely impacted; two were moderately impacted. The site displayed many characteristics of a stressed plant community. Site biodiversity was moderate, and ecological integrity was low. There was abundant evidence of risks to long-term site productivity, indicating the site was supporting a low level of production and placing the site at risk of further reductions in productive capacity. Soil and water conservation was moderate. A complete vegetation cover reduced the risk of surface soil erosion, although undulating slopes indicated that areas could be susceptible to soil loss with surface disturbance. The low tree density created a high risk for losses both through the soil profile and in surface losses.
Toxicity Testing	R	The majority of test species did not grow well in the natural soil when compared with the reference sites. There was agreement between the two approaches.
Soil Chemical and Physical Analysis	Y	This non-eroded site had organic matter levels that were similar to the reference sites. Some of the fertility parameters (e.g. Ca and Mg) were found to be deficient.
Litter Bag Decomposition Analysis	G	Neither the rate of decomposition (k) nor total annual decomposition was significantly different between CC-04 and REFmean, indicating low to no impact at CC-04.

CC-06: Ranked Moderately Impacted

Two of the four LOE were ranked moderately impacted and the toxicity was split between moderate and severe. The site displayed many characteristics of a plant community in transition; the site soil contained adequate organic matter for seedling development and growth but showed signs of potential nutrient deficiency; test species did not perform well in this soil during the toxicity testing. Overall, this site was ranked moderately impacted.

Line of Evidence	Rank		Comments
Plant Community Assessment 	Y		One indicator was ranked severely impacted; three were moderately impacted. The site displayed many characteristics of a plant community in transition. Site biodiversity and ecological integrity were moderate. Long-term productivity was low, suggesting the site supported an intermediate level of production and placing the site at moderate risk of further reductions in productive capacity. Soil and water conservation was moderate. A complete vegetative cover reduced the risk of surface soil erosion. However, the rolling terrain indicated that areas could be susceptible to soil loss with any surface disturbance. The site was flagged as being at moderate risk in terms of long-term carrying capacity.
Toxicity Testing	Y	R	The test species had moderate to greatly reduced performance in the natural soil when compared to the reference sites.
Soil Chemical and Physical Analysis	Y		With the well-developed LFH horizons, soils at this site contained adequate organic matter for seedling development and growth. However, there was some evidence for potential Mg and available N deficiencies.
Litter Bag Decomposition Analysis	R		The rate of decomposition (k) was lower at CC-06 than REFmean and indicated a severe impact on this ecosystem function. This could lead to increasingly larger differences in total decomposition over time.

CC-07: Ranked Severely Impacted

Three of the LOE were ranked severely impacted. The plant community was stressed; plants and invertebrates did not perform well in this soil during the toxicity testing; and, the soil displayed potential Mg and N deficiencies. Overall, this site was ranked severely impacted.

Line of Evidence	Rank	Comments
Plant Community Assessment 	R	Two indicators were ranked severely impacted; two were moderately impacted. This site displayed many characteristics of a stressed plant community. Site biodiversity was moderate, and ecological integrity was low. Long-term productivity was low, suggesting a risk of further reductions in productive capacity with soils subject to losses through the profile. The very low supplies of organic matter for the soil organic pool flagged this site as being at moderate risk in terms of long-term carrying capacity. Soil and water conservation was moderate. The almost complete vegetative cover and the low slopes reduced the risk of surface loss through erosion. However, low tree and tall shrub densities created a high risk for soil losses in solution through the soil profile and for surface losses during heavy rainfall.
Toxicity Testing	R	With the exception of white spruce, the majority of test species did not grow well in the natural soil when compared with the reference sites. There was agreement between the two approaches with the exception of red clover performance.
Soil Chemical and Physical Analysis	Y	With the well-developed LFH horizons, soils at this non-eroded site contained adequate organic matter for seedling development and growth. However, there was some evidence for potential magnesium and available nitrogen deficiency.
Litter Bag Decomposition Analysis	R	Rate of decomposition (k) was lower at CC-07 than REFmean and indicated a severe impact on ecosystem function. This could lead to increasingly larger differences in total decomposition over time.

CC-08: Ranked Moderately Impacted

Three of the LOE were ranked moderately impacted. The site displayed many characteristics of a stressed plant community; test species performed moderately well in the site soil during toxicity testing, the soil showed some evidence for potential Mg and N deficiency; and, the rate of decomposition was moderately impacted. Overall, this site ranked moderately impacted.

Line of Evidence	Rank	Comments
Plant Community Assessment 	R	Two indicators were ranked severely impacted; two were moderately impacted. The site displayed many characteristics of a stressed plant community. Biodiversity was moderate; the presence of common hairgrass cover on over half of the site reduced the available seedbed for the establishment of a variety of forest species. Ecological integrity was moderate; the site conditions remained favourable for tolerant and potentially invasive species, but species richness was high and there was almost complete vegetation cover. Long-term productivity was low, suggesting a risk of further reductions in productive capacity. Soil and water conservation was low. The steep slopes and low tree density increased the risk of soil losses through the soil profile and during heavy rainfall events.
Toxicity Testing	Y	The majority of test species had moderately reduced or similar performance in natural soil when compared to the reference sites. There was agreement between the two approaches.
Soil Chemical and Physical Analysis	Y	With the well-developed LFH horizons, soils at this non-eroded site contained adequate organic matter for seedling development and growth. However, there was some evidence for potential magnesium and available nitrogen deficiency.
Litter Bag Decomposition Analysis	Y	The rate of decomposition (k) was lower at CC-08 than REFmean and indicated a moderate impact on ecosystem function. This could lead to increasingly larger differences in total decomposition over time.

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CON-01: Ranked Moderately Impacted		
Three of the four LOE were ranked moderately impacted. The site displayed many characteristics of a plant community in transition. Although the soil characterization was ranked moderately impacted, the soil has been affected by fire. The rate of decomposition was severely impacted. Overall, this site was ranked moderately impacted.		
Line of Evidence	**Rank**	**Comments**
Plant Community Assessment 	Y	Three indicators were ranked moderately impacted; one was low to not impacted. This site displayed many characteristics of a plant community in transition. The moderate scores for biodiversity, ecological integrity and long-term productivity suggested that conditions may be improving or that site productivity is inherently modest. Soil and water conservation were not at risk.
Toxicity Testing	Y	The performance of northern wheatgrass and white spruce in the natural soil was similar to the reference sites, while the performance of goldenrod and red clover was moderately to greatly lower. There was agreement between the two approaches.
Soil Chemical and Physical Analysis	Y	This site is ranked moderately impacted. Historical fire has affected the nature of the organic matter and the surface organic horizons. The site may also be deficient in available nitrogen, potassium and magnesium.
Litter Bag Decomposition Analysis	R	Rate of decomposition (k) was lower at CON-01 than REFmean and indicated a severe impact on ecosystem function. This could lead to increasingly larger differences in total decomposition over time.

CON-02: Ranked Severely Impacted

All four LOE were ranked severely impacted. The plant community was stressed; the test species did not perform well in the site soil during toxicity testing; the site was eroded and the soil was nutrient deficient as for CC-01. Overall, this site was ranked severely impacted.

Line of Evidence	Rank	Comments
Plant Community Assessment 	R	Two indicators were ranked severely impacted; one, moderately impacted; and one low to not impacted. This site displayed many characteristics of a stressed plant community. Site biodiversity and ecological integrity were low. The scarcity of shade tolerant and sensitive cryptogam indicators and the presence of many metal and acid tolerant indicators suggested that site conditions were unfavourable for many common forest species. Long-term productivity was moderate. Soil and water conservation were not at risk; the level terrain, moderate plant cover, and high density of trees and tall shrubs reduced the erosion potential.
Toxicity Testing	R	The majority of test species had moderate to greatly reduced performance in the natural soil when compared with the reference sites. There was agreement between the two approaches with the exception of the performances of white spruce and red clover.
Soil Chemical and Physical Analysis	R	The soils at this highly impacted site were low in surface organic matter, deficient in nutrients, and subject to freeze-thaw processes that could impede regeneration.
Litter Bag Decomposition Analysis	R	Rate of decomposition (k) was lower at CON-02 than REFmean and indicated a severe impact on ecosystem function. This could lead to increasingly larger differences in total decomposition over time.

CON-03: Ranked Moderately Impacted

Two of the four LOE were ranked severely impacted. The site displayed many characteristics of a plant community in transition; the test species did not perform well in the site soil during toxicity testing; the moderately eroded soil did not display the characteristics of a good growth medium; and, the rate of decomposition was severely impacted, resulting in an overall site rank of moderately impacted.

Line of Evidence	Rank	Comments
Plant Community Assessment 	Y	Three indicators were ranked moderately impacted; one was severely impacted. This site displayed many characteristics of a plant community in transition. Site biodiversity was moderate. Ecological integrity was low, with many acid- and metal-tolerant indicators present, little evidence of tree regeneration and a very high invasive grass cover. Long-term site productivity and soil and water conservation were moderate. The low tree density on this silt-rich soil raised concerns of erosion, which were mitigated by the level terrain and high plant and leaf litter cover.
Toxicity Testing	Y R	The performance of the majority of test species was moderately to greatly reduced in natural soil when compared with the reference sites. There was agreement between the two approaches, with the exception of the performance of red clover and goldenrod in natural soil.
Soil Chemical and Physical Analysis	Y	The imperfectly drained soils at this moderately eroded site did not have an adequate LFH horizon for seedling germination and growth. Although the relict mineral soil horizons were well developed and have a relatively high clay content, there was a potential available nitrogen deficiency at this site.
Litter Bag Decomposition Analysis	R	Rate of decomposition (k) was lower at \CON-03 than REFmean and indicated a severe impact on ecosystem function. This could lead to increasingly larger differences in total decomposition over time.

CON-05: Ranked Severely Impacted

Two of the three LOE that were evaluated were ranked moderately impacted. The plant community was stressed; plants and invertebrates did not perform well in this soil during the toxicity testing; the site was eroded and the soil did not display the characteristics of a good growth medium. Overall, this site was ranked severely impacted.

Line of Evidence	Rank	Comments
Plant Community Assessment 	R	Two indicators were ranked severely impacted; two were moderately impacted. This site displayed many characteristics of a stressed plant community. Site biodiversity was moderate, with a potentially invasive grass species covering almost half of the site. Ecological integrity was low; there was little evidence of successful regeneration. Long-term site productivity was moderate. Soil and water conservation was at risk due to erosion concerns generated by low tree density, extremely low leaf litter cover, and a low volume of downed woody debris. However, these effects were mitigated by continuous plant cover and low slopes.
Toxicity Testing	Y R	The majority of test species did not grow well in the natural soil, when compared with the reference sites. There was agreement between the two approaches only with respect to northern wheatgrass performance.
Soil Chemical and Physical Analysis	Y	The imperfectly drained soils at this moderately eroded site did not have an adequate LFH horizon for seedling germination and growth. Although the relict mineral soil horizons were well developed and had a relatively high clay content, there was a potential available nitrogen deficiency at this site. The differences in extractable iron and manganese may also indicate a potential problem.
Litter Bag Decomposition Analysis	-	Not evaluated

CON-06: Ranked Severely Impacted

Three of the four LOE were ranked moderately impacted. The plant community was stressed; the test species did not perform well in the site soil during toxicity testing; the site was eroded; and, there was a very low carbon content in the soil as for CC-01. These factors contributed to an overall site ranking of severely impacted.

Line of Evidence	Rank	Comments
Plant Community Assessment 	R	Three indicators were ranked severely impacted; one was moderately impacted. This site displayed many characteristics of a stressed plant community. Site biodiversity was moderate. Although species diversity was high, the lack of species dominance may reflect overall poor growing conditions. Downed woody debris was very low, and the site showed strong evidence of disturbance. Ecological integrity, long-term site productivity and soil and water conservation were low. Although there was a high density of trees and tall shrubs, the large portion of exposed mineral substrate and steep slopes greatly increased the potential for surface soil loss through erosion.
Toxicity Testing	R	The performance of the test species was moderately to greatly reduced when compared to the reference sites. There was agreement between the two approaches with the exception of the performance of red clover and goldenrod.
Soil Chemical and Physical Analysis	Y	The imperfectly drained soils at this moderately eroded site did not have an adequate LFH horizon for seedling germination and growth. Although the relict mineral soil horizons were well developed, there was a very low organic carbon content. The Ca:Mg ratio was lower than most sites in this study, suggesting a potential nutrient imbalance.
Litter Bag Decomposition Analysis	R	Rate of decomposition (k) was lower at CON-06 than REFmean and indicated a severe impact on ecosystem function. This could lead to increasingly larger differences in total decomposition over time.

CON-08: Ranked Severely Impacted

All four LOE were ranked severely impacted. The plant community was stressed; the test species did not perform well in the site soil during toxicity testing; the site was eroded and the soil was nutrient deficient as for CC-01. Overall, this site was ranked severely impacted.

Line of Evidence	Rank	Comments
Plant Community Assessment 	R	All four indicators were ranked as severely impacted. This site displayed many of the characteristics of a stressed plant community. Site biodiversity was low, reflecting low species richness and diversity, the complete absence of downed woody debris and trees, and evidence of disturbance. Ecological integrity was low. Over 20% of the surface was exposed mineral substrate. Long-term site productivity and soil and water conservation were low. The negligible leaf litter cover, the absence of downed woody debris, shrub and tree cover and the negligible seasonal additions of organic matter limited subsoil water retention and created a high erosion risk.
Toxicity Testing	R	The majority of test species, with the exception of northern wheatgrass, did not grow well in the natural soil when compared with the reference sites. There was agreement between the two approaches.
Soil Chemical and Physical Analysis	R	The imperfectly drained soils at this highly eroded site did not have an adequate LFH horizon for seedling germination and growth. The surface mineral soil horizons (up to and including the Ae horizon) were also completely eroded from this site. The structural integrity of the remaining mineral horizons at this site was very poor. The Ca:Mg ratio was lower than most sites in this study, suggesting a potential nutrient imbalance. This site was also low in both available nitrogen and magnesium.
Litter Bag Decomposition Analysis	R	Rate of decomposition (k) was lower at CON-08 than at REFmean and indicated a severe impact on ecosystem function. This could lead to increasingly larger differences in total decomposition over time.

FB-01: Ranked Severely Impacted

Three of the four LOE were ranked severely impacted. The plant community was stressed; plants and invertebrates did not perform well in this soil during the toxicity testing; the soil, although uneroded, displayed evidence of fire. Overall, this site was ranked severely impacted.

Line of Evidence	Rank	Comments
Plant Community Assessment 	R	Two indicators were ranked moderately impacted; two were severely impacted. This site displayed many characteristics of a stressed plant community. Biodiversity and ecological integrity were low. The low numbers of overall species and indicators of improving conditions suggested that the soil and site conditions did not favour the successful germination and establishment of a range of forest plant species. Long-term site productivity was moderate. The lack of poplar presence and small size of downed woody debris raised concerns that the rate of nutrient availability may not match the needs of a fully occupied site. Soil and water conservation were moderate with the high tree density and level terrain mitigating the erosion risk.
Toxicity Testing	R	With the exception of white spruce, the test species did not grow well in the natural soil when compared with the reference sites. There was agreement between the two approaches with the exception of goldenrod.
Soil Chemical and Physical Analysis	Y	The Podzolic soil was typical of the modal soils on the glacio-fluvial outwash within the Sudbury region. These soils generally have a relatively low moisture holding capacity. Although this site was not eroded, the amount of charcoal in the LFH horizon is indicative of a high intensity fire in the recent past. The relatively high fertility on this site may be a reflection of an increase in nutrient availability from the surface organic layers following the historical fire.
Litter Bag Decomposition Analysis	R	The rate of decomposition (k) was lower at FB-01 than REFmean and indicated a severe impact on ecosystem function. This could lead to increasingly larger differences in total decomposition over time.

FB-02: Ranked Moderately Impacted

Two LOE were ranked severely impacted; two LOE were ranked low to not impacted. The site displayed many characteristics of a relatively stable plant community and the soil shows minimal impact. However, the rate of decomposition was severely impacted, and the test species performed poorly in the site soil during the toxicity testing, resulting in an overall site rank of moderately impacted.

Line of Evidence	Rank	Comments
Plant Community Assessment 	G	Three indicators were ranked low to not impacted; one was moderately impacted. This site displayed many characteristics of a relatively stable plant community, with good scores for ecological integrity, long-term site productivity and soil and water conservation. The moderate scores for site biodiversity may reflect the dense tree cover, which provided continuous shade, thereby reducing the diversity of understory species.
Toxicity Testing	Y R	All of the test species had moderate to greatly reduced performance in the natural soil. There was agreement between the two approaches with the exception of the performance of goldenrod.
Soil Chemical and Physical Analysis	G	The well drained soil at this site showed minimal impact from either fire or mining.
Litter Bag Decomposition Analysis	R	The rate of decomposition (k) was lower at FB-02 than REFmean and indicated a severe impact on ecosystem function. This could lead to increasingly larger differences in total decomposition over time.

<table>
<tr><th colspan="3">FB-03: Ranked Moderately Impacted</th></tr>
<tr><td colspan="3">Three of the four LOE were ranked moderately impacted. The site displayed many characteristics of a plant community in transition; test species performed moderately to poor (severely impacted) in site soil during the toxicity testing; the soil exchange complex chemistry and site fertility showed moderate impact; and, the rate of decomposition was moderately impacted. Overall, the site was ranked moderately impacted.</td></tr>
<tr><td>Line of Evidence</td><td>Rank</td><td>Comments</td></tr>
<tr><td>Plant Community Assessment
</td><td>Y</td><td>All four indicators were ranked moderately impacted. The site displayed many characteristics of a plant community in transition, with moderate scores for site biodiversity, ecological integrity, long-term site productivity, and soil and water conservation. Species diversity was low partially due to the dominance of low sweet blueberry on half the site. Many indicators suggested that tree cover was patchy or intermittent, and that site conditions remained less than favourable for common forest species. The erosion risks created by moderately steep slopes and a low density of woody material were mitigated by a high plant and moderate leaf litter cover. The low downed woody debris volumes and low density of woody material reduced the additions of organic matter to the soil and the on-site supplies of residual organic matter.</td></tr>
<tr><td>Toxicity Testing</td><td>Y R</td><td>With the exceptions of red clover and goldenrod in natural soil, the performance of the plant species was similar to the reference sites. There was agreement between the two approaches.</td></tr>
<tr><td>Soil Chemical and Physical Analysis</td><td>Y</td><td>The Podzolic soil was typical of the modal soils on the glacio-fluvial outwash within the Sudbury region. These soils generally have a relatively low moisture holding capacity. Although this site was not eroded, the amount of charcoal in the LFH horizon is indicative of a medium intensity fire in the recent past. Both soil exchange complex chemistry and site fertility indicate moderate impact.</td></tr>
<tr><td>Litter Bag Decomposition Analysis</td><td>Y</td><td>The rate of decomposition (k) was lower at FB-03 than REFmean and indicated a moderate impact on ecosystem function. This could lead to increasingly larger differences in total decomposition over time.</td></tr>
</table>

FB-05: Ranked Moderately Impacted

Two of the four LOE were ranked moderately impacted. The toxicity testing indicated that plants grew fairly well in this soil; the plant community assessment concluded that this was a community in transition; the site was not eroded, although fertility endpoints and exchange complex chemistry were impacted; and, the rate of decomposition low to not impacted. Overall, this site was ranked moderately impacted.

Line of Evidence	Rank	Comments
Plant Community Assessment 	Y	Two indicators were ranked moderately impacted, one ranked low to not impacted, and one ranked severely impacted. This site displayed many characteristics of a plant community in transition. Biodiversity was low, and ecological integrity was moderate. There was a high coniferous component and negligible cover of introduced species or exposed mineral soil, but poor species richness. Long-term site productivity was moderate, with the high percentage of dieback lowering the score. Soil and water conservation was not at risk, with the low average slope and high woody species density reducing erosion risk. Annual additions of organic matter to the soil appeared reasonable, suggesting that continuous improvement would occur at this site.
Toxicity Testing	G Y	The performance of the majority of test species in natural soil was similar to or moderately lower than the reference sites with the exception of goldenrod. There was agreement between the two approaches, with the exceptions of northern wheatgrass and goldenrod performance.
Soil Chemical and Physical Analysis	Y	The Podzolic soil is typical of the modal soils on the glacio-fluvial outwash within the Sudbury region. These soils generally have a relatively low moisture holding capacity. Although this site was not eroded, the charcoal fragments in the H layer indicate a moderate intensity historical fire. Both soil exchange complex chemistry and site fertility indicated moderate impact.
Litter Bag Decomposition Analysis	G	Neither rate of decomposition (k) nor total annual decomposition was significantly different between FB-05 and REFmean, indicating low to no impact at FB-05.

FB-06: Ranked Moderately Impacted

One LOE was ranked severely impacted and one was ranked moderately impacted. The test species performed well in the site soil during toxicity testing, and the soil showed minimal impact. The plant community displayed many characteristics of a plant community in transition and the rate of decomposition was severely impacted. Overall, this site ranked moderately impacted.

Line of Evidence	**Rank**	**Comments**
Plant Community Assessment 	Y	Three indicators were ranked moderately impacted; one was low to not impacted. This site displayed many characteristics of a plant community in transition. Biodiversity, ecological integrity and long-term site productivity were moderate. The major concerns were the high percentage of dieback and low volume of downed woody material. However, tree and shrub densities were high, as were tree heights and the number of decomposition classes present. Soil and water conservation was not at risk; a high percentage of leaf litter and plant cover and a high density of trees and tall shrubs minimized the erosion potential created by moderate slopes.
Toxicity Testing	G	The majority of test species, with the exception of goldenrod, grew well in the natural soil. There was agreement between the two approaches.
Soil Chemical and Physical Analysis	G	The well-drained soil at this site showed minimal impact from either fire or mining.
Litter Bag Decomposition Analysis	R	The rate of decomposition (k) was lower at FB-06 than REFmean and indicated a severe impact on ecosystem function. This could lead to increasingly larger differences in total decomposition over time.

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3.12 Step 2: Interactions Between Lines of Evidence

The interactions between the four LOE were assessed in Step 2 of Objective #1. During the Step 1 evaluation of the LOE, the metal content of the soil was *not* considered and the LOE were ranked irrespective of the metal concentrations in the soil. During the Step 2 evaluation, the total metal levels and the bioavailable metal levels measured in the soil at each site were included with the other soil chemistry parameters. Three statistical approaches were applied to examine interactions between the LOE. The approaches, methods and results of these evaluations are presented in the following section. The three types of analyses used in Step 2 were as follows:

1. A multiple linear regression analysis was used to determine if there was a relationship between soil chemical parameters and soil toxicity;
2. A multiple linear regression analysis was used to determine if there was a relationship between the toxicity endpoints (root and shoot length of the four plant species), the bioavailable metal concentrations (EDTA and $CaCl_2$ extractants) and the calcium derived from CEC;
3. A canonical correspondence analysis (CCA) was used to determine whether there was a relationship between the soil chemistry parameters and the plant community parameters.

The results of the first two analyses are presented in Appendix GH-1 and the results of the third analysis are in Appendix GH-2. An overview of the methods and results of these approaches is provided in the following sections. However, prior to undertaking the statistical analyses, the measurement variables had to be reduced to a manageable number. This process is described in the next section.

3.12.1 Creating Independent Soil Variables

The data set for this objective included over 60 variables for only 22 sites, which introduced a considerable amount of auto correlation between variables. This auto-correlation prevented a simple multiple linear regression approach from being utilized, especially with the highly numeric variable range in the auto-correlated raw data. To minimize the auto-correlation in the large data set, the information contained in these variables was grouped into factors. The data were first standardized by converting the raw data to Z-scores (Standard Ecological Variables) to normalize the central location and average variability of the data set. This Z-score transformation did not affect the skewness and kurtosis observed in the original data. The pooling of the variables into factors was based on a separation of variable type, variable source (i.e. anthropic or geogenic), textural or fertility relationships. This approach is similar to the concept of Technogenic Factors as discussed in the European literature (Kasimov and Lychagin 2002). Grouping of the chemical variables was undertaken by cluster analysis by Dr. G. Spiers at Laurentian University in a stepwise fashion shown in Figure 3-29.

The soil chemistry results (presented in Section 3.4) were pooled into different groupings, and each group was considered an independent variable. To achieve this, related soil parameters were grouped together. The chemical parameters included in each group are summarized in Table 3.33. The table is followed by a description of each of the factors with more details on the rationale for the grouping of soil parameters. The results of the three different statistical analyses follow the description of the independent soil factors.

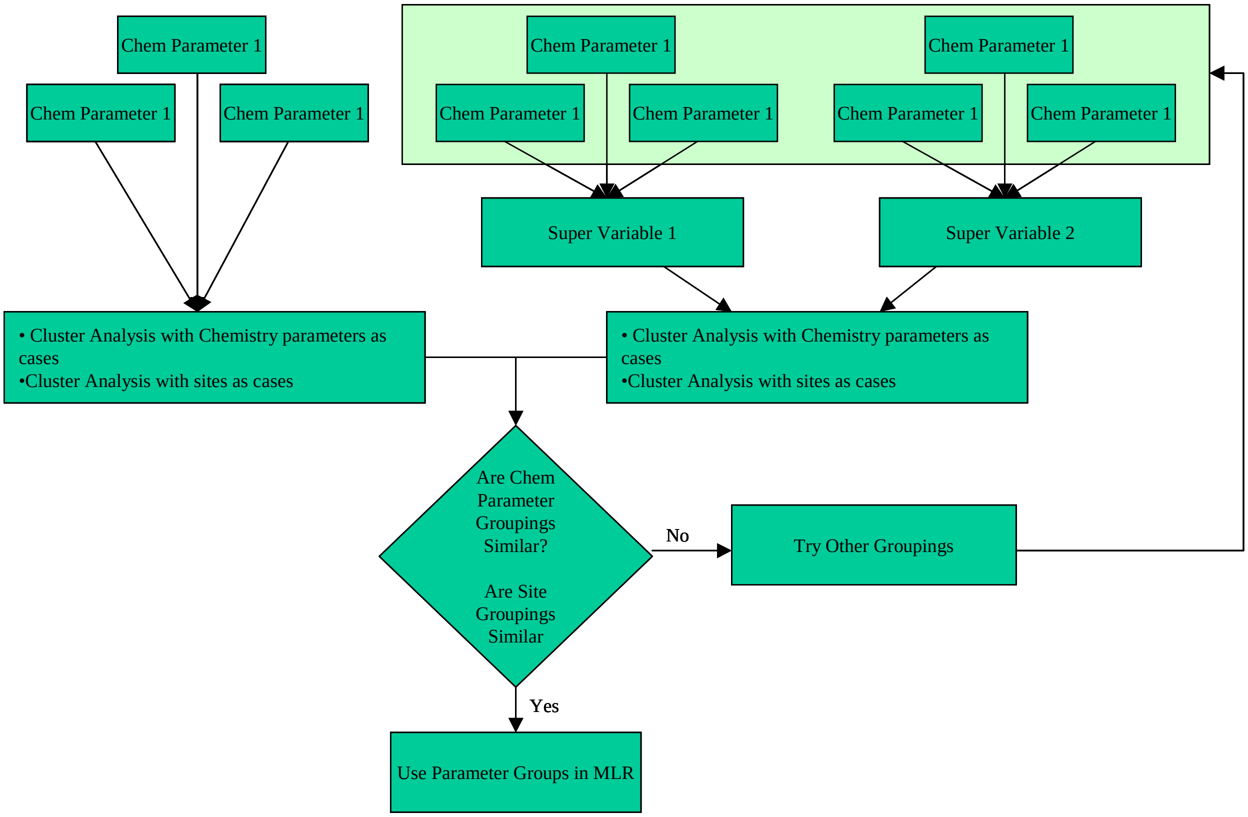


Figure 3-29 Summary of the Step-wise Process Taken for Cluster Analysis of the Soil Chemistry Results

Table 3.33 Summary of the Groupings of Soil Chemistry Parameters for Multiple Linear Regression Analyses

Grouping	Soil Chemistry Parameter(s)	Description
Technogenic Load Factor (TLF)	As, Cd, Co, Cu, Pb, Ni, Se	The concentrations of the chemicals of concern (COC) obtained by total metal analysis.
Geogenic Load Factor (GLF)	Al, Ba, Be, B, Ca, Cr, Fe, La, Mg, Mn, P, V, Zn	The total concentration data for the metals (total metal analysis) in the soil matrix, not assumed to be influenced by addition as aerosols from regional smelting activities.
Technogenic Bioavailability Factor (TBF)	As, Cd, Co, Cu, Pb, Ni, Se	The concentration of COC obtained by a simple water extract with analysis of the resultant solutions by ICP-MS analysis. TBF was also combined with sulphur (TBF+S), a measure of the bioavailable sulphur, a component of the acidic rainout and a probable soluble salt product in many of the smelter fallout materials. The comparison between TBF and TBF+S allows the influence of available sulphur, probably as sulphate ion, to be examined. TBF was also combined with the pH factor (TBF+pHF).
Geogenic Bioavailability Factor (GBF)	Al, Ba, B, Ca, Fe, Mg, Mn, S, Zn	The concentration of accurately quantified metals obtained by a simple water extract of the soil matrix. The abundance of these elements was not assumed to be influenced by addition as aerosols from regional smelting activities. Although sulphur may be both of geogenic and smelter origin, the element was included in the initial factor calculation. A second factor without sulphur (GBF-S) has been included in the results to allow the influence to be examined.
pH Factor (pHF)	pH	The pH factor (both water and calcium chloride extracts) was computed in a manner identical to that for all other variable groups. However, because pH is but a measure of hydrogen ion concentration in solution additional factors, namely TBF+pH and FF+pH, these were also computed to enable the effect of hydrogen ion concentration on toxicological response to be examined in exactly the manner as the water-soluble bioavailable ionic species.
Cation Exchange Factor (CECF)	Cation exchange capacity	The data for both cation exchange capacity (CEC) and exchangeable cations (K, Na, Ca, Mg) were standardized, pooled and averaged to calculate this factor.
Organic Matter Factor (OMF)	C, N	This factor consisted of total amounts of carbon and nitrogen in organic matter.
Parent Material Depositional Factor (PMDF)	Bulk density, Soil texture (% sand, silt, clay)	The soil parent materials included in this study are of till, glaciofluvial and glaciolacustrine origin. Measures such as soil texture and bulk density reflect the mode of deposition of these soil-forming materials.
Fertility Factor (FF)	N, Nitrate, P, K, Mg	A series of routine agronomic soil fertility analyses completed on all samples from this study were used to develop a soil fertility factor. These data included water extractable ammonia (as N), available nitrate, extractable phosphorus, potassium, and magnesium. This factor was also combined with the pH factor called FF+pHF.
Extractable Metals (DPTA)	Fe, Mn	This factor includes DPTA extractable Fe and Mn. This factor was also combined with the fertility factor (called DPTA+FF).

Summary of Factor Development

Technogenic Load Factor (TLF)

The concentrations of the chemicals of concern (As, Cd, Co, Cu, Pb, Ni, Se) and Hg in samples taken from soil cores by partial digestion with concentrated nitric acid, followed by ICP-MS analysis of resultant solutions were used to develop this factor. Comparison of concentrations in cores with those obtained from homogenized samples is provided in Section 3.3.3. All raw data were standardized and then pooled into this one factor.

Geogenic Load Factor (GLF)

The concentration of the metals in the soil matrix not assumed to be influenced by addition as aerosols from regional smelting activities obtained by partial acid digestion with concentrated nitric acid and ICPMS analysis of resultant solutions was used to develop this factor. The metals in this suite included Al, Ba, Be, B, Ca, Cr, Fe, La, Mg, Mn, P, V and Zn. The balance of the measured elements, although probably of geogenic origin, was excluded from the development of this factor because accurate quantification in many of the samples was not possible as levels were below the methodological detection limits. All raw data were standardized and then pooled into this one factor.

Technogenic Bioavailability Factor (TBF)

The concentration of the chemical of concerns (As, Cd, Co, Cu, Pb, Ni and Se) obtained by a simple water extraction and analysis of the resultant solutions by ICP-MS analysis were used to develop this factor. Bioavailable sulphur, a component of the acidic rainout and a probable soluble salt product in many of the smelter fallout materials was included in a second factor, TBF+S, to allow the influence of available sulphur, probably as sulphate ion, to be examined. All raw data were standardized and then pooled into this one factor.

Geogenic Bioavailability Factor (GBF)

The concentration of the metals obtained by a simple water extraction of the soil matrix, with analysis of the resultant solutions by ICP-MS, was used to develop this factor. The abundance of these elements were not assumed to be influenced by addition as aerosols from regional smelting activities. The metals included in this suite are Al, Ba, B, Ca, Fe, Mg, Mn, S, and Zn. Although sulphur may be both of geogenic and smelter origin, the element was included in the initial factor calculation because to date this element has been excluded from all of the discussions in the risk assessment process. However, a second (GBF-S) factor was included in the results to allow the influence to be examined. The balance of the analyzed elements, although probably of geogenic origin, was excluded from the development of this factor because accurate quantification in many of the samples was not possible as levels were below the methodological detection limits. All raw data were standardized and then pooled into this one factor.

pH Factor (pHF)

The determination of pH in both water and calcium chloride extractions is a common measurement in the environmental sciences, so common that the actual importance and value of the measurement is commonly over-valued. The potentially toxic effect of high levels of metals is due to their speciation in the solution phase, with actual species distribution being commonly dependent on the pH of the soil solution. Thus, the pH factor is computed in a manner identical to that for all other variable groups. However, because pH is a measure of hydrogen ion activity in solution additional factors, namely TBF+pH and FF+pH, were also computed to enable the effect of hydrogen ion activity on toxicological response. All raw data were standardized and then pooled into the pH factor.

Cation Exchange Factor (CECF)

Both cation exchange capacity (CEC) and exchangeable cations (K, Na, Ca, Mg) were used to generate this factor. All raw data were standardized and then pooled into this one factor.

Organic Matter Factor (OMF)

The key parameters available for analysis were the total amounts of carbon and nitrogen. These parameters were standardized and pooled into this one factor.

Parent Material Depositional Factor (PMDF)

The soil parent materials included in this study are of till, glaciofluvial and glaciolacustrine origin. The textural and bulk density measurements reflect the mode of deposition of these soil-forming materials; all textural measurements were included with the density estimate in the calculation of this factor. All raw data were standardized and then pooled into this one factor.

Fertility Factor (FF)

A series of routine agronomic soil fertility analyses completed on all samples from this study were used to develop a soil fertility factor. These data included available nitrate, extractable phosphorus, potassium and magnesium. Levels of extractable DPTA were also included in the calculation of the fertility related factors. The data obtained by water extraction for ammonia (as N) from the bioavailability assessment were also included. The estimates of DPTA extractable iron and manganese were not included in the calculation of FF. A factor including the DPTA data (FF+DPTA) and a DPTA factor (DPTA) were also calculated to allow examination of the various extractants individually. All raw data was standardized and then pooled into these factors as appropriate.

3.12.2 Analysis 1: Relationship Between Physical and Chemical Parameters and Toxicity Endpoints

A multiple linear regression (MLR) was used to examine relationships between soil chemical parameters and soil toxicity. A report detailing the approach, methods and results for the analysis is presented in Appendix GH-1 and is summarized below.

The toxicological endpoints of interest were terrestrial plant growth (*i.e.* root and shoot length) and reproductive success of earthworms (*i.e.* number of juveniles). Preliminary examination of the results showed that inclusion of the root and shoot weight did not influence the results of the MLR analysis.

The parameters were standardized using Z scores and then made into variables by pooling all values and calculating an average. The mean of the standardized values for each of the defined groups was used in the multiple linear regression analysis. For example, if the standardized values for nickel, copper and cadmium were 0.5, 0.4 and 0.3, respectively, the group value was the sum of these values (1.2) divided by the number of components (three in this case) to obtain 0.4. This method of grouping increased the degrees of freedom and decreased the collinearity between many of the measured soil chemistry parameters. The selection of models was based on the following criteria:

1. Start with a model that had at least a R^2 of 0.6 (*e.g.*, best three-variable model);
2. Give attention to the stability of the variables as each additional variable is added and/or removed. This process was halted, and the model selected, when either no more significant variables ($p<0.05$) entered the model, or the inclusion and/or exclusion of additional variables caused no substantial change in the R^2 or F value (up to a maximum of eight variables);
3. During the stepwise selection process, if a model was found to have one or more insignificant variables after addition/removal of variables, the process was halted, and the model selected for the endpoint of interest was the last modification of the model that contained only significant variables, regardless of R^2 (e.g., $R^2 = 0.55$); and,
4. If all models had a R^2 of less than 0.6, start with the maximum-variable model and the model selected for the endpoint of interest was the one that had the most variables that were all significant.

This means that in order for a variable to be included in the model it had to be statistically significant (p-value < 0.05).

The toxicity endpoints used in the analysis are presented in Table 3.34. The combination of endpoints and soil chemistry groupings provided 11 different models that could be evaluated.

Table 3.34 Summary of Toxicity Endpoints Considered in Multiple Linear Regression Analysis

Species	Endpoint	Type of Soil	Type of Normalized Data
Goldenrod	Root Length	Natural	Standardized Ecological Variables (Z-scores)
	Shoot Length	Natural	Standardized Ecological Variables (Z-scores)
Red Clover	Root Length	Natural	Standardized Ecological Variables (Z-scores)
	Shoot Length	Natural	Standardized Ecological Variables (Z-scores)
Northern Wheatgrass	Shoot Length	Natural	Standardized Ecological Variables (Z-scores)
White Spruce	Shoot Length	Natural	Standardized Ecological Variables (Z-scores)
Northern Wheatgrass	Root Length	pH-amended	Standardized Ecological Variables (Z-scores)
	Shoot Length	pH-amended	Standardized Ecological Variables (Z-scores)
Red Clover	Root Length	pH-amended	Standardized Ecological Variables (Z-scores)
	Shoot Length	pH-amended	Standardized Ecological Variables (Z-scores)
E. andrei	Number of Juveniles	pH-amended	Standardized Ecological Variables (Z-scores)

Results of Analysis 1

The detailed results of the analysis are detailed in Tables GH1.B4-10 of Appendix GH1. Here, the R^2 for each individual model is listed along with the significant variables (p-value < 0.05) from which the model was comprised. Over 160 different equations or models were generated to examine the relationships between the endpoints measured in the toxicity tests and the physical and chemical soil parameters (see Appendix GH1 for more details). After reviewing these models the following are the generalized observations:

- The technogenic load factor (TLF), which includes the COC, was inversely related to the root and shoot length of goldenrod, northern wheatgrass and red clover in natural site soil.
- The fertility of the site soil was a positive factor in the growth of goldenrod and red clover.
- White spruce behaved differently from the other plants. In most situations, regression models could not be developed but where they could, organic matter (OM) and the soil matrices other

than the COC (OM and geogenic load factor (GLF)) were the only significant variables in the models; OM was positively related while the GLF was inversely related to the plant endpoints.

- Parent material depositional factor (PMDF) was consistently present in the models for goldenrod, northern wheatgrass and red clover indicating a positive relationship.
- The shoot length of white spruce had an inverse relationship to pH (pH was present in 9 out of 11 models). Lower pH was associated with increased shoot length. No explanation is apparent for this relationship.
- Depending on the plant type, either fertility (positive relationship) or pH and fertility combined (inverse relationship) contributed to the shoot length for goldenrod, red clover and white spruce.
- The number of earthworm juveniles in pH-amended soil was also evaluated. Only four of eleven combinations of parameters could be developed into models with significant interactions. Where the models were established, the geogenic metals (GLF) had an inverse relationship, while pH seemed to have the most influence (positive) on earthworm production.

In almost all scenarios, the COC and soil properties (TLF and PMDF) were inversely related to the root and shoot length of plants from the toxicity testing LOE. Many of the models included either soil fertility (FF) or pH (pHF) as important factors. Although results for white spruce were quite different compared to the other plant species, the results suggest that the concentration of metals in the site soil along with pH, soil texture and fertility were the primary factors related to the toxicity endpoints measured.

3.12.3 Analysis 2: Evaluation of the Relationship Between Toxicity endpoints, Bioavailability of Metals and Soil Fertility

A multi-linear regression analysis was conducted comparing root and shoot length of the four plant species in natural soil with the bioavailable metal concentrations of As, Pb, Cu, Mn and Ni and the Ca derived from the cation exchange capacity extraction. The metal concentrations were measured using two analytical extractions; EDTA and $CaCl_2$. The criteria used to derive the MLR models were the same as those described in the Phase Two analysis (Appendix GH-1).

The selection of models was based on the following criteria:

1. Start with a model that had at least a R^2 of 0.6 (e.g., best three-variable model);
2. Give attention to the stability of the variables as each additional variable is added and/or removed. This process was halted, and the model selected, when either no more significant variables ($p<0.05$) entered the model, or the inclusion and/or exclusion of additional variables caused no substantial change in the R^2 or F value (up to a maximum of eight variables);
3. During the stepwise selection process, if a model was found to have one or more insignificant variables after addition/removal of variables, the process was halted, and the model selected for the endpoint of interest was the last modification of the model that contained only significant variables, regardless of R^2 (e.g., $R^2 = 0.55$); and,
4. If all models had a R^2 of less than 0.6, start with the maximum-variable model and the model selected for the endpoint of interest was the one that had the most variables that were all significant.

This means that in order for a variable to be included in the model it had to be statistically significant (p-value < 0.05).

The toxicological endpoints of interest were terrestrial plant growth (*i.e*. root and shoot length).

Once again the parameters were standardized using Z scores and then made into variables by pooling all values and calculating an average, as described in Section 3.12.2.

The toxicity endpoints evaluated are presented in Table 3.35.

Table 3.35 Summary of Toxicity Endpoints Considered in the Second Multiple Linear Regression Analysis

Species	Endpoint	Type of Soil	Type of Normalized Data
Goldenrod	Root Length	Natural	Standardized Ecological Variables (Z-scores)
	Shoot Length	Natural	Standardized Ecological Variables (Z-scores)
White Spruce	Root Length	Natural	Standardized Ecological Variables (Z-scores)
	Shoot Length	Natural	Standardized Ecological Variables (Z-scores)
Red Clover	Root Length	Natural	Standardized Ecological Variables (Z-scores)
	Shoot Length	Natural	Standardized Ecological Variables (Z-scores)
Northern Wheatgrass	Root Length	Natural	Standardized Ecological Variables (Z-scores)
	Shoot Length	Natural	Standardized Ecological Variables (Z-scores)

Results of Analysis 2

The detailed results of the analysis are detailed in Tables GH1.B4-10 of Appendix GH1. Here, the R^2 for each individual model is listed along with the significant variables (p-value < 0.05) from which the model was comprised. In total, 16 models (8 endpoints with 2 extraction techniques) were evaluated and the results are presented in the report in Appendix GH1. After reviewing these models the following are the generalized observations:

- The results for goldenrod show that manganese and CEC Ca were present in all models for root and shoot length. While CEC Ca was positively related, Mn was negatively related to root and shoot length.
- No models could be derived for root length of white spruce. Mn, Pb and Cu appeared to have a negative relationship with shoot length of white spruce.
- As, which was the common metal present in all models for root and shoot length of red clover, was inversely related to the endpoints.
- Cu was present (inverse relationship) in all models for root and shoot length for northern wheatgrass.
- Overall, CEC Ca was strongly positively correlated with root and shoot length of most plants, being present in 8 of the 16 models.

In almost all scenarios, CEC Ca was related to the root and shoot length of plants from the toxicity testing LOE. For the goldenrod models, Mn and CEC Ca were the only two factors. Many of the models also included either arsenic or lead as important factors. No significant regression models were generated for white spruce and the soil parameters in this analysis. Copper was consistently inversely related with the northern wheatgrass toxicity endpoints.

3.12.4 Analysis 3: Evaluation of the Relationship Between Plant Community and Physicaland Chemical Parameters

Analysis 1 (MLR) identified that the main physical and chemical factors related to the toxicity endpoints measured during the toxicity testing were the COC, parent material and fertility (TLF, PMDF and FF). In the second analysis, the fertility factors of CEC Ca and Mn were identified as being related to plant growth. The aim of Analysis 3 was to determine which factors were related to the plant community assemblage at the study sites. Canonical correspondence analyses (CCA) (ter Braak 1986) was used to determine whether the parameters identified in Analysis 1 were also related to the plant communities at the sites. A soil ecologist, Dr. Mark St. John of Laurentian University, completed the analysis. Details of the methods and results are presented in the report in Appendix GH2.

Canonical correspondence analyses (ter Braak 1986) were performed using percent cover of plant types (trees, tall shrubs, low shrubs, forbs and cryptograms) and TLF, PMDF and FF variables. PMDF did not conform to the normality assumption required for CCA and so a non-parametric method known as Non-metric multidimensional scaling (MDS) was performed in parallel with the CCA. MDS is free of assumptions of normality but is unconstrained by environmental factors. Relationships between the community and the environment can only be inferred post-hoc. However, concordance between the CCA and MDS would suggest that CCA results are valid and that violations of the assumption of normality of the CCA method are not grave enough to warrant abandoning the results. Species and sites scores were scaled for plotting. The significance of results was determined using Monte Carlo permutations (1000).

Results of Analysis 3

The hypothesis that plant assemblage composition was related to TLF and FF was supported by CCA ($F3,^4 = 0.844$, $p = 0.013$). The first two canonical axes explained 37.8 % of the total variance in the data. TLF was significantly correlated ($p < 0.01$) with the first two canonical axes ($R^2 = 0.432$) as was FF ($p = 0.050$, $R^2 = 0.287$). PMDF was not a significant explanatory factor for the plant assemblages.

Similarly, MDS ordination uncovered nearly identical relationships between species, sites and the factors TLF and FF. The general distribution of species, sites and their relationships to factors differed little between the CCA and MDS. TLF was significantly correlated ($p = 0.019$) with the first two canonical axes ($R^2 = 0.381$) as was FF ($p = 0.034$, $R^2 = 0.333$). Thus, interpretation of the results from CCA were deemed valid for these data.

Conclusion

Metals of concern (TLF) were significantly related to the structure of plant communities at the study sites. Sites with the highest TLF scores (high COC levels) included CC-02 and CC-03, while CC-06 and REF03 had some of the lowest TLF scores. Trees and low shrubs had higher relative percent cover when TLF was high, while forb cover was negatively related to TLF. Soil nutrients, or fertility (FF), were also a significant determinant of plant assemblage structure.

3.12.5 Step 2 Summary

During Step 2, the interactions between the chemistry parameters measured in the site soil, the toxicity test endpoints and the plant community LOE were assessed. Three statistical approaches were applied to examine the relationship between these measurements.

Analysis 1 showed that the COC and soil properties were inversely related to the root and shoot length of plants from the toxicity testing. Other factors identified as important were soil fertility (positive relationship) and pH (inverse relationship). In this analysis the results for the tree species tested (white spruce) were quite different compared to the other plant species.

Analysis 2 showed that some of the fertility factors, such as Mn, were inversely related to root and shoot length. Alternatively, Ca was positively related to those endpoints. Other factors that were identified as important were arsenic, lead and copper (all inversely related). No models could be derived to describe the root and shoot lengths of white spruce.

Analysis 3 found that the COC (factor TLF) were significantly related to the structure of plant communities at the study sites. Trees and low shrubs had higher relative percent cover when TLF was high while forb cover was negatively related to TLF. This result mirrors the finding in Analysis 1, providing agreement between the laboratory studies and the field survey. As with the toxicity testing, soil nutrients were also a significant determinant of plant assemblage structure. The soil properties (PMDF) were not a significant explanatory factor for the plant assemblages.

The combination of these three analyses show that, at the 22 sites established to evaluate Objective #1 of the ERA, the level of COC in the soil was related to the toxicity to plants as measured in toxicity tests and to the structure of the plant communities surveyed at the sites. Fertility was also a factor of importance.

3.13 Step 3: Determining Whether Metals in Soil are the Most Likely Cause of Observed Impairment

In Step 1, the LOE were evaluated individually to determine an impact ranking for each LOE. The ranks for the LOE were then considered together and a final ranking was given to each test site using a weight of evidence (WOE) approach. The Step 1 ranking approaches evaluated the LOE irrespective of the metal concentration of the site soil. In Step 2, the physical and chemical soil characteristics were grouped into categories and statistically compared with the plant community assessment and toxicity testing LOE. The aim of these assessments was to determine whether the soil chemistry was correlated to the LOE results. The purpose of this final step, Step 3, was to determine if the concentration of metals at the test sites were the most likely cause of ecosystem impairment and to determine if there are other factors that may be contributing to the overall toxicity (or lack of toxicity) of the site soil.

In Step 3, the sites were coloured according to their final site rank (from Step 1). For each transect, the sites were ordered according to their total metal concentration, water leach metal concentration and their distance from the smelter. To do this, all of the site numbers were arranged into the following categories:

- Order of total metals (Cu, Ni, As, Cd, Co, Pb, Se) from the highest to lowest concentration.

- Order of water extracted (plant available) metals (Cu, Ni, As, Cd, Co, Pb, Se) from the highest to the lowest concentration.

- Distance from the related smelter (distance of CC sites to Copper Cliff smelter; distance of CON sites to Coniston smelter, distance of FB sites to Falconbridge smelter) from the closest to the farthest away.

When most of the sites on a transect had concentrations of total and water leach metals below background values (Table F MOE, 1997) for a particular metal the metal (total and water leach) was excluded from the evaluation for that transect *(e.g.*, Pb). This approach provided a visual representation of the data to qualitatively examine the role of total metals, water leach metals and distance from the smelter with each site ranking.

The results of these groupings for each transect are discussed in the following sections.

3.13.1 Copper Cliff Transect

Table 3.36 shows the sites along the Copper Cliff transect coloured according to their final site rank after the integration of the 4 LOE (Table 3.32) and arranged according to total metals, water leach metals and distance from the smelter.

Table 3.36 Ranking of Copper Cliff Sites Sorted by Total Metals, Water Leach Metals and Distance from Smelter

Total metals (descending from highest concentration by metal)							Water leach metals (descending from highest concentration)*					Distance from Smelter (closest to farthest)
Ni	**Cu**	**As**	**Cd**	**Co**	**Pb**	**Se**	**Ni**	**Cu**	**As**	**Cd**	**Co**	
CC-03	CC-03	CC-03	CC-01	CC-03	CC-03	CC-03	CC-02	CC-02	CC-01	CC-02	CC-03	CC-03
CC-01	CC-01	CC-01	CC-04	CC-02	CC-01	CC-01	CC-04	CC-03	CC-04	CC-01	CC-02	CC-01
CC-02	CC-02	CC-02	CC-02	CC-01	CC-02	CC-02	CC-03	CC-01	CC-07	CC-04	CC-01	CC-02
CC-04	CC-04	CC-04	CC-03	CC-04	CC-04	CC-04	CC-01	CC-04	CC-02	CC-03	CC-04	CC-04
CC-07	CC-07	CC-07	CC-07	CC-07	CC-07	CC-07	CC-06	CC-07	CC-03	CC-06	CC-07	CC-07
CC-06	CC-06	CC-06	CC-06	CC-06	CC-08	CC-06	CC-07	CC-06	CC-06	CC-07	CC-06	CC-06
CC-08	CC-08	CC-08	CC-08	CC-08	CC-06	CC-08	CC-08	CC-08	CC-08	CC-08	CC-08	CC-08

*The majority of sites had levels of plant-available Pb and Se that were below detectable limits.
** These are the final site rankings after the integration of the 4 LOE (Table 3.32)

Table 3.37 provides a summary of the physical and chemical soil parameters relative to the final site rank.

Table 3.37 Summary of Soil Chemistry Parameters for the Copper Cliff Transect in Relation to the Overall Site Ranking

Site	Soil Development	Organic Matter	SECC*	Fertility
CC-01	++	-	-	+
CC-02	-	+	+	++
CC-03	++	-	+	+
CC-04	-	-	-	+
CC-06	-	+	+	+
CC-07	-	-	-	+
CC-08	-	-	+	+

\+ indicates rank of moderate impact
++ indicates rank of severe impact
\- indicates low to not impacted
*Soil Exchange Complex Chemistry
** These are the final site rankings after the integration of the 4 LOE (Table 3.32)

Table 3.36 strongly suggests that the metal levels in the soil along the Copper Cliff transect were related to the severity of site impact. The evidence can be summarized as follows:

- Total metal levels: The sites with the highest total metal levels were consistently the most impacted sites. The highest total metal levels occurred in soil from CC-01, CC-02 and CC-03.

The next highest metal concentrations occurred in CC-04 and CC-07. The sites with the lowest concentration of total metals were CC-06 and CC-08. Only CC-08 was ranked as moderately impacted (no sites on this transect were ranked as not impacted).

- Water extracted metal levels: The highest plant available metal concentrations were generally in the most impacted site: CC-01, CC-02, CC-03 and CC-04. Site CC-08 had the lowest concentrations of metals for all COC. Again, only CC-08 was ranked as moderately impacted.
- Distance from smelter: The order of the sites from closest to farthest from the Copper Cliff smelter were CC-03, CC-01, CC-02, CC-04, CC-07, CC-06 and CC-08. The most severely impacted sites (red) were closest to the smelter, while CC-08 was the most distant and only site ranked moderately impacted.

Along the Copper Cliff transect, the sites that had the highest total and water extracted metal concentrations were always the sites that were ranked as severely impacted. The one site along the Copper Cliff transect that was ranked moderately impacted (CC-08) was the site with the lowest metal concentrations and was furthest away from the smelter. Two of the sites were eroded (CC-03 and CC-01) with poor soil development, but both of these sites also had high metal levels. All of the sites along the Copper Cliff transect had low fertility, but only one (CC-02) had such low fertility that it was likely impeding recovery of the plant community.

3.13.2 Coniston Transect

Table 3.38 shows the final rankings after the integration of the 4 LOE (Table 3.33) of the Coniston sites arranged according to total metals, water extracted metals and distance from the smelter.

Table 3.38 Ranking of Coniston Sites Sorted by Total Metals, Water Leach Metals and Distance from Smelter

Total metals (descending from highest concentration by metal)			Water leach metals (descending from highest concentration)*			Distance from Smelter (closest to farthest)
Ni	**Cu**	**As**	**Ni**	**Cu**	**As**	
CON-02	CON-02	CON-03	CON-08	CON-01	CON-08	CON-06
CON-08	CON-03	CON-02	CON-06	CON-03	CON-03	CON-08
CON-03	CON-05	CON-05	CON-02	CON-08	CON-01	CON-02
CON-05	CON-08	CON-01	CON-05	CON-02	CON-05	CON-03
CON-01	CON-01	CON-08	CON-01	CON-05	CON-02	CON-05
CON-06	CON-06	CON-06	CON-03	CON-06	CON-06	CON-01

*Most of sites had below detectable limits of water leach Pb and Se.
** These are the final site rankings after the integration of the 4 LOE (Table 3.32)

Table 3.39 shows a summary of the results of the physical and chemical soil parameters relative to final site rank. CON-07, the historically limed and re-greened site, is not included in the final site ranking but is discussed in detail in Section 3.14.

Table 3.39 Summary of the Soil Chemistry Parameters for the Coniston Transect in Relation to the Overall Site Ranking

Site	Soil Development	Organic Matter	SECC*	Fertility
CON-01	-	+	-	+
CON-02	+	++	++	+
CON-03	+	+	+	-
CON-05	+	+	+	+
CON-06	+	++	+	-
CON-08	++	++	+	++

+ indicates rank of moderate impact
++ indicates rank of severe impact
- indicates low to not impacted
*Soil Exchange Complex Chemistry
** These are the final site rankings after the integration of the 4 LOE (Table 3.32)

Four sites along the Coniston transect were ranked as severely impacted and two sites were ranked moderately impacted. There was no consistent order of the sites along this transect when arranged by the different parameters. The evidence relating to metals as a causative factor in the impairment of sites on the Coniston transect can be summarized as follows:

- Total metal levels: With the exception of Cu, Ni and As, the remaining COC were at background levels in the site soils. The site with the highest concentrations of total Cu and Ni was CON-02, which was ranked at severly impacted. Only CON-03 had As levels above background concentrations. The sites with the lowest concentrations of metals were CON-01 and CON-06.

- Water leach metal levels: The levels of plant available Ni mirrored the impact ranking of the sites. CON-08 had the highest levels, followed by CON-06 and CON-02. The sites with the lowest Ni levels from the water leach analysis were CON-01 and CON-03, which were both ranked moderately impacted.

- Distance from smelter: The severely impacted sites tended to be closest to the smelter, although CON-05 was an exception.

With the exception of one site, CON-01, all the sites on the Coniston transect were eroded to some degree. This erosion was likely caused by the historic loss of plant cover associated with the high levels of SO_2 in the past.

The site closest to the smelter, CON-06, was ranked as severely impacted. The plant community, toxicity testing and soil characteristics all indicated a site that was not favourable for plant growth. The decomposition assessment indicated that the microbial community was also severely impacted. The soil at this site was eroded with very little organic matter. The fertility and exchange complex chemistry pointed to a site where the soil was relict mineral soil with an eroded LFH horizon. The metal levels at this site were very low, amongst the lowest on the transect. Historically, in the areas around this site, very high concentrations of metals were measured in the soils (P. Beckett, personal communication). It seems likely that this site historically contained very high concentrations of metals that have now been removed by erosion along with the soil that would provide a growth medium.

CON-08, the next closest to the smelter was also ranked as severely impacted. All four indicators in the plant community assessment were impacted; most of the species in the toxicity testing did not perform well and, with the exception of northern wheatgrass, did not improve as a result of pH amendment of the soil. The site faired poorly in the soil physical and chemical analysis and decomposition was severely impaired. CON-08 had the third highest concentration of total Ni, but the highest concentration of water leached Ni on the Coniston transect. To determine whether the current metal concentrations were a contributing factor to the continued impact at CON-08, other soil properties important to metal bioavailability were compared. The pH at CON-08 (4.5 water/slurry and 3.96 $CaCl_2$) and the Ca levels were extremely low (0.82 cmol(+)/kg). The uptake of metals by organisms may be physiologically moderated by pH and competing cations such as Ca (Allen, 2002). It is likely that the low pH and Ca levels at CON-08 were impeding recovery and that the lower metal levels were a result of the highly eroded nature of the site.

CON-02 was the next closest site to the Coniston smelter and again, all four LOE were ranked as severely impacted. The total metal levels were the highest along the transect, although the water leach concentrations were lower, being third or fourth highest. There appeared to be a relationship between elevated total metal levels and impact at CON-02. Other factors likely contributing to the toxicity of the site soil included very low Ca levels (0.3 cmol(+)/kg); a lack of organic matter; low exchange capacity; decreased fertility levels (ammonium, K and Mg) and low pH levels (4.41 water/slurry and 3.76 $CaCl_2$).

CON-03 and CON-05 were located at a moderate distance from the smelter, with CON-03 being somewhat closer, but ultimately less impacted than CON-05. Total and water leach metals were not consistently lower at either site; however, the plant community was ranked moderately impacted at CON-03, while it was severely impacted at CON-05. Both sites were eroded in the organic horizons. Factors contributing to the greater impacts at CON-05 may include the soil exchange complex chemistry and fertility.

Despite the fact that soil pH at CON-01 was the lowest of the transect (4.34 water/slurry and 3.44 $CaCl_2$), this site was ranked as moderately impacted, and many of the categories evaluated were close to being in the low to no impact category. The metal levels at this site were marginally above background concentrations (MOE, 1997). The plant community at CON-01 was in transition; three out of the four indicators were ranked yellow and one was green. In the toxicity testing, most species performed quite well. The soil physical and chemical characterization at the site showed little impairment, although some fertility endpoints were deficient and there was evidence of a forest fire. The decomposition rate was severely impacted. On the whole, this site appeared to be recovering well from historical impacts.

3.13.3 Falconbridge Transect

Table 3.40 shows the final rankings after the integration of the 4 LOE (Table 3.32) of the Falconbridge sites arranged according to total metals, water leach metals and distance from the smelter.

Table 3.40 Ranking of Falconbridge Sites Sorted by Total Metals, Water Leach Metals and Distance from Smelter

Total metals (descending from highest concentration by metal)							Water leach metals (descending from highest concentration)*					Distance from Smelter (closest to farthest)
Ni	**Cu**	**As**	**Cd**	**Co**	**Pb**	**Se**	**Ni**	**Cu**	**As**	**Cd**	**Co**	
FB-01	FB-01	FB-01	FB-02	FB-02	FB-01	FB-01	FB-01	FB-02	FB-02	FB-01	FB-02	FB-05
FB-02	FB-02	FB-02	FB-01	FB-01	FB-02	FB-02	FB-02	FB-01	FB-06	FB-02	FB-01	FB-01
FB-06	FB-05	FB-05	FB-06	FB-06	FB-06	FB-06	FB-03	FB-06	FB-01	FB-03	FB-06	FB-02
FB-05	FB-06	FB-06	FB-03	FB-05	FB-05	FB-05	FB-05	FB-05	FB-05	FB-06	FB-05	FB-06
FB-03	FB-03	FB-03	FB-05	FB-03	FB-03	FB-03	FB-06	FB-03	FB-03	FB-05	FB-03	FB-03

*Most of sites had below detectable limits of water leach Pb and Se.
** These are the final site rankings after the integration of the 4 LOE (Table 3.32)

Table 3.41 provides a summary of the physical and chemical soil parameters relative to the final site rank.

Table 3.41 Summary of the Soil Chemistry LOE for the Falconbridge Transect

Site	Soil Development	Organic Matter	SECC*	Fertility
FB-01	-	+	+	-
FB-02	-	-	-	-
FB-03	-	++	+	+
FB-05	-	+	+	+
FB-06	-	-	+	-

\+ indicates rank of moderate impact
++ indicates rank of severe impact
\- indicates low to not impacted
*Soil Exchange Complex Chemistry
** These are the final site rankings after the integration of the 4 LOE (Table 3.32)

The sites along the Falconbridge transect were generally ranked moderately impacted with the exception of one site (FB-01), which was considered severely impacted. Although four out of five sites were ranked as moderately impacted, there appeared to be an association between the metals in the soil and the level of impact. The results can be summarized as follows:

- Total metal levels: The sites with the highest concentration of total metals were always either FB-01 or FB-02. The next highest concentration of total metals occurred in FB-05 or FB-06. FB-03 had the lowest concentration of metals for all COC except Cd.

- Water leach metal levels: The highest plant available metal levels for Ni, Cu and Co occurred in either FB-01 or FB-02. The highest available As and Cd levels were present at FB-02. The lowest levels of the water leach COC always occurred in either FB-05 or FB-03. The exception to this was Ni, which was slightly higher at FB-03.

- Distance from smelter: The order of the sites from closest to farthest from the Falconbridge smelter was FB-05, FB-01, FB-02, FB-06 and FB-03. Although closer than FB-01, FB-05 is slightly upwind from the smelter (based on predominant summer wind direction) and the rest of the sites are in a downwind direction. FB-01 was the only severely impacted site.

None of the sites along the Falconbridge transect were eroded. There was evidence of a forest fire at all sites except FB-02 and FB-06.

The site that had the highest total and water leach metal levels (FB-01) was the only site that was ranked severely impacted. This site had high soil organic matter and adequate nutrients available; however, the plant community assessment, decomposition survey and toxicity testing indicated that plants and microbes were highly impacted. The pH of this site was very low (4.1 water slurry and 3.21 $CaCl_2$). A pH below 4.7 has been identified in Sudbury as likely limiting to plant growth (P. Beckett personal communication). However, one of the reference sites (REF-02) had a comparably low pH, yet had a healthy plant community, functioning decomposition cycle and soil that performed well during the toxicity tests. There is evidence at FB-01 of a high intensity fire in the recent past. The impacts on the plant community at FB-01 were likely due to its proximity to the Falconbridge smelter, high concentrations of metals in the soil and lingering effects from the high intensity fire.

FB-02 had some of the highest metal concentrations along this transect. This site had a healthy (not impacted, ranked green) plant community and adequate nutrient levels in the soil, but a poor decomposition rate. To help determine why this site, with metal levels comparable to FB-01 appeared to be much less impacted, the chemistry of the sites was examined. The most striking differences between the sites were the Ca concentration and the soil pH. The uptake of metals by organisms may be physiologically moderated by pH and by competing cations such as Ca^{2+} (Allen, 2002). The Ca levels at FB-02 were 16 times higher than at FB-01 and were in fact higher than any of the other sites along this transect (ten times higher than FB-03, seven times higher than FB-05 and three times higher than FB-06). Competing cations, of which Ca^{2+} is one, are among the key soil properties controlling the partitioning of metals in soil solution (Allen, 2002). The increased levels of Ca at FB-02 were possibly competing for metal uptake, so the in-situ metal bioavailability was low.

The other factor that was different between FB-01 and FB-02 was soil pH. As mentioned above the pH of the soil at FB-01 was low (4.1 water slurry and 3.21 $CaCl_2$) compared to FB-02 (4.77 water slurry and 4.05 $CaCl_2$). During the toxicity testing, red clover and northern wheatgrass did not perform well in the natural site soil from FB-01, but once the pH of the soil was raised, both species preformed as well as they did at the reference sites. This was not the case at FB-02, where amending the pH did not alter the results (both species performed moderately well). White spruce grew well at FB-01 but very poorly at FB-02. White spruce has moderate requirements for both nutrients and water, and has a high tolerance to acidic conditions. The differing performance of white spruce at FB-01 and FB-02 may reflect tolerance to low pH and low Ca conditions.

The site closest to the Falconbridge smelter was FB-05. Although close to the smelter, the total and water extractable metal levels were among the lowest on this transect. Of the four LOE, none were ranked as highly impacted. The direction of the wind was likely the key factor in the lack of metals and observed impact at this site. Although in close proximity to the smelter, this site was located upwind rather than downwind of the smelter (Appendix GB-12) and did not have as significant a metal loading as the downwind sites.

The sites furthest from the smelter, FB-06 and FB-03, often had the lowest concentration of metals in the soil. Three LOE were ranked as moderately impacted at FB-03 and the toxicity testing LOE was given a split ranking between moderately and severely impacted. There was evidence of a forest fire, which may have caused a recent disturbance to the plant community. FB-03 was observed to have a plant community in transition. Despite being a moderate site in terms of slope, the erosion risks were offset by the high plant and litter cover. The plant community seemed to be recovering despite the soil pH, which was low enough to be considered limiting to plant growth (4.24 water slurry and 3.64 $CaCl_2$). The soil from FB-03 lacked organic matter and some fertility parameters but despite this, the species performed well during the toxicity testing, with the exceptions of red clover and goldenrod. Although FB-06 was ranked as moderately impacted overall, the toxicity testing LOE and soil chemistry were both ranked as low to not impacted. This site had high organic matter and fertility levels. However, the decomposition LOE was impacted, and the pH of the soil was low enough to be considered limiting to plant growth (4.37 water slurry and 3.48 $CaCl_2$). Metal levels were not contributing to the moderate impact at either of these sites.

3.13.4 Summary

By assessing the final ranking of the sites (from Step 1) in conjunction with the metal levels (total and water extracted) and distance from the smelter along each transect, the Step 3 evaluations revealed the following:

- Along the Copper Cliff transect, the sites with high metal levels (both total and water extracted) were also the sites closest to the smelter. There was an association between elevated metal concentrations in the site soil on the Copper Cliff transect and the level of site impact. The low fertility levels at some sites were also likely associated with the lack of recovery at some sites.
- Along the Falconbridge transect, the sites closest to the smelter in a downwind direction had the highest metal levels. One of these sites, (FB-01), was ranked as severely impacted; the other, (FB-02), was moderately impacted. Both of these sites contained elevated metal levels but pH and Ca levels were higher at FB-02. There was an association between sites with high metal levels in the soil and the level of impact. Ca and pH were identified as important factors in the bioavailability of the metals.
- Along the Coniston transect, the sites with the highest metal levels were generally the ones that were most impacted. Where this was not the case, the site tended to be highly eroded. Many of the sites along this transect were severely to moderately eroded. At the severely impacted sites that were close to the smelter, the metal levels were often low. Metal levels along this transect tended to be lower than along the other transects. Historically, it is likely that the metal levels and SO_2 levels were high at these sites, resulting in a loss of vegetation, which led to a loss of soil due to erosion. When the soil was lost at these sites, the metals were also lost. The relict soil layers that remain are nutrient deficient and lack organic matter. The importance of increased

> pH and Ca levels in the recovery of the plant community was also apparent along this transect as Ca was very low. Although the sites with high metal concentrations along this transect were impacted, there were also other sites located close to the smelter where the metal levels were low and the sites were severely impacted. Other factors contributing to the impact level at these sites were low pH, erosion, low nutrient levels, and lack of organic matter in the soil. The results of this transect illustrated the role that factors other than soil metal levels can play in preventing vegetation recovery.

When Steps 1 and 2 were evaluated together, it appeared that the COC in the Sudbury region were impeding the recovery of a self-sustaining plant community. Other factors identified as important were fertility endpoints, pH of the soil, incidence of forest fires in the past, concentration of Ca and the levels of organic matter in the soil.

3.14 Studies Conducted to Investigate the Role of pH on Sudbury Soils During Objective #1

Soil pH was not a chemical of concern in this risk assessment, but is known to have a major influence on metal availability and the suitability of soils for plant growth. Within the Sudbury region, the range of soil pH has been found to be below that which is typically considered suitable for plant growth ($pH < 5.0$). This section provides a discussion of how the role of soil pH was addressed in this study.

pH is an indication of alkalinity or acidity and is measured by the number of hydrogen ions present in the soil solution. The pH of soil indicates the activity of hydrogen ions held on the clay and organic matter particles. The strength of an acid is described using a pH scale. This is a logarithmic scale based on the "powers of ten" so a pH of 6.0 is 10-times more acidic than pH 7.0 and a pH 5.0 is 100-times more acidic than pH 7.0. Acidity influences a whole range of soil characteristics such as the nature of the variable charge, nutrient availability, microbial activity and the release of metals (Ashman and Puri, 2002).

The degree of soil acidity has a direct influence on plant growth. Many northern ecosystems have very acidic soils: the pH values of the soils of the Boreal forests may be 4 or less. Due to industrial emissions in the region, certain Sudbury area soils were acidified from an expected normal pH range of 4.5 to 5.5 to levels of pH 3.2 to 4.4. An acid soil can restrict the root and top growth of plants, reduce the availability of plant nutrients, decrease desirable biological activity, and increase the availability of metals in the soil. Growing plants remove calcium and magnesium from the soil, the lost calcium and magnesium is replaced by hydrogen and aluminium, resulting in an increase in soil acidity.

Soil acidity can change when hydrogen or aluminum ions bound by soil and organic matter particles are replaced with calcium or magnesium ions. The application of dolometric limestone can promote desirable biological activity and improve the structure of some soils.

During the Objective #1 studies, the role of soil pH was evaluated in two ways that will be discussed in the following sections: a) toxicity tests were conducted in natural and pH-amended soils, and b) the characteristics of a historically limed field site (CON-07) were compared to an adjacent non-limed site (CON-08).

3.14.1 Impact of pH-Amendment of Soils on the Toxicity Testing Results

The aim of the toxicity testing LOE was to assess the performance of the toxicity test species in soils collected from the test and reference sites. Ideally, plant species used in toxicity tests should be native to the Sudbury region and have previously established standardized test methods. Unfortunately to date, the vast majority of Canadian standardized toxicity tests use plant species of agricultural importance which will not grow well in the soil from the Sudbury region. The soil properties which are inherent in the Sudbury region (i.e. low soil pH) are naturally outside the range for optimum growth of most plant species of agricultural importance. Since standardized tests were not available for more acid tolerant plant species, a compromise was reached whereby selected plant species were concurrently grown in natural site and pH-amended soils (pH of approximately 5.2).

The toxicity tests in pH-amended site soils were conducted following the same protocols as those performed in natural site soil. Toxicity tests in pH-amended soil were conducted using northern wheatgrass and red clover. The pH of the site soils was adjusted using similar procedures to those used to adjust the pH of the formulated artificial soil as described in Section GF10-2.0 (Appendix GF-10). The details of the approach taken to assess toxicity in the pH-amended soil are presented in Appendix GF-10.

The purpose of using pH-amended soil was to try to better understand the influence of low soil pH on soil toxicity as well as the relationship of pH with metal toxicity. Although the results of the toxicity tests in pH-amended soil were not incorporated into the site rankings, they do contribute valuable information on the effect of low soil pH to these test organisms. Raising the pH of the soil often reduced its toxicity, but did not alleviate it altogether.

The results (data and percent change in plant measurements) from the toxicity testing in natural and pH-amended soil for Northern Wheatgrass and Red Clover are shown in Table 3.42-3.45 a (biomass and emergence); b (shoot length and weight); and, c (root length and weight). The results are expressed as a percentage change relative to the unamended site soils. To illustrate the effect of pH amendment on plant performance, the change in emergence and biomass (i.e., the sum of root and shoot weights) as a result of the pH amendment was plotted against distance to the nearest smelter (Figure 3-30). Soils from site FB01 had the lowest in-situ pH and elevated total metals (pH = 3.2, Cu = 909 mg/kg and Ni = 535 mg/kg); and red clover did not emerge in the natural soil from this site. After soil amendment, 92% of the seedlings emerged and produced 5.5mg of biomass. These values have not been included in Figures 3-30a-d as they cannot reliably be expressed as a percentage change from zero.

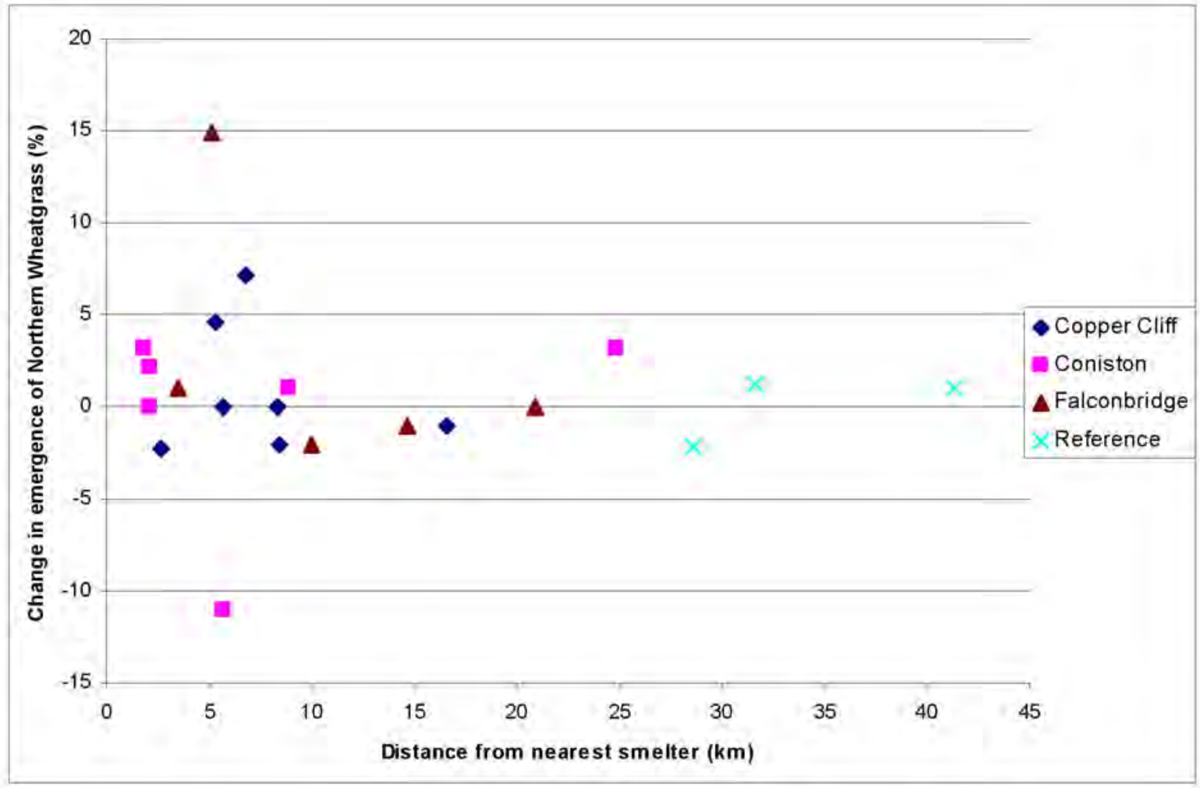


Figure 3-30a Change in emergence of Northern Wheatgrass following pH amendment.

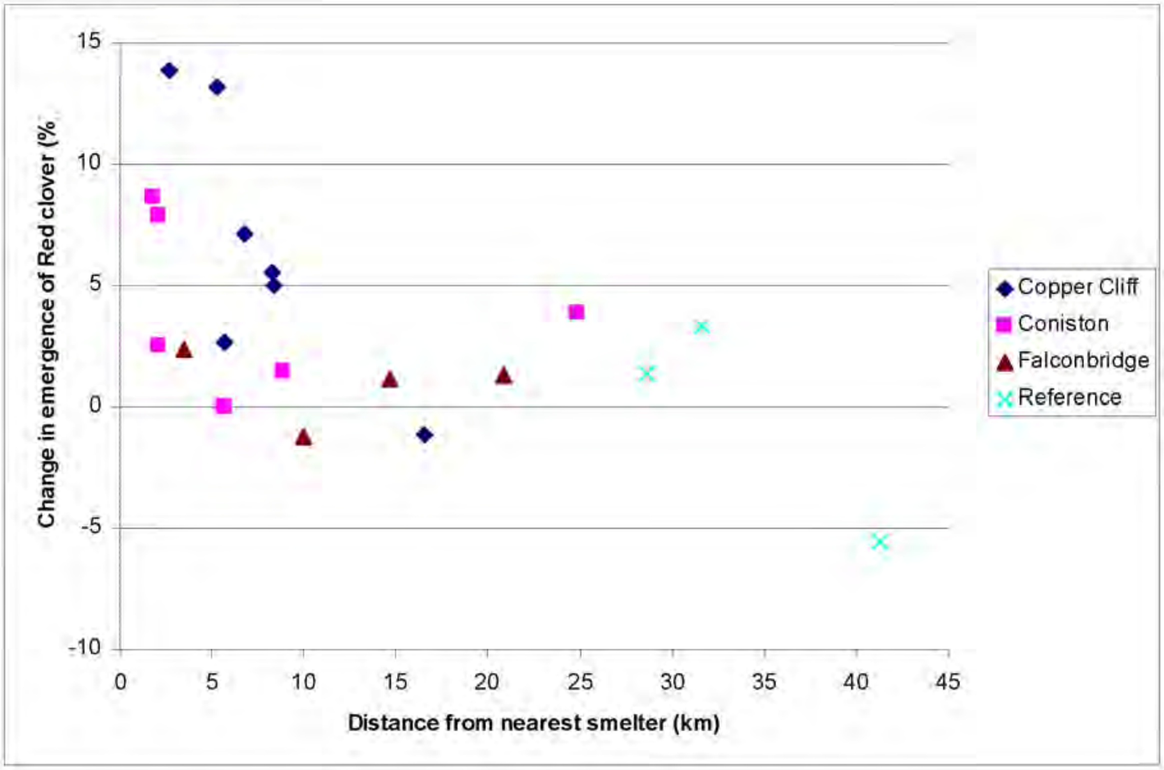


Figure 3-30b Change in emergence of Red Cover following pH amendment.

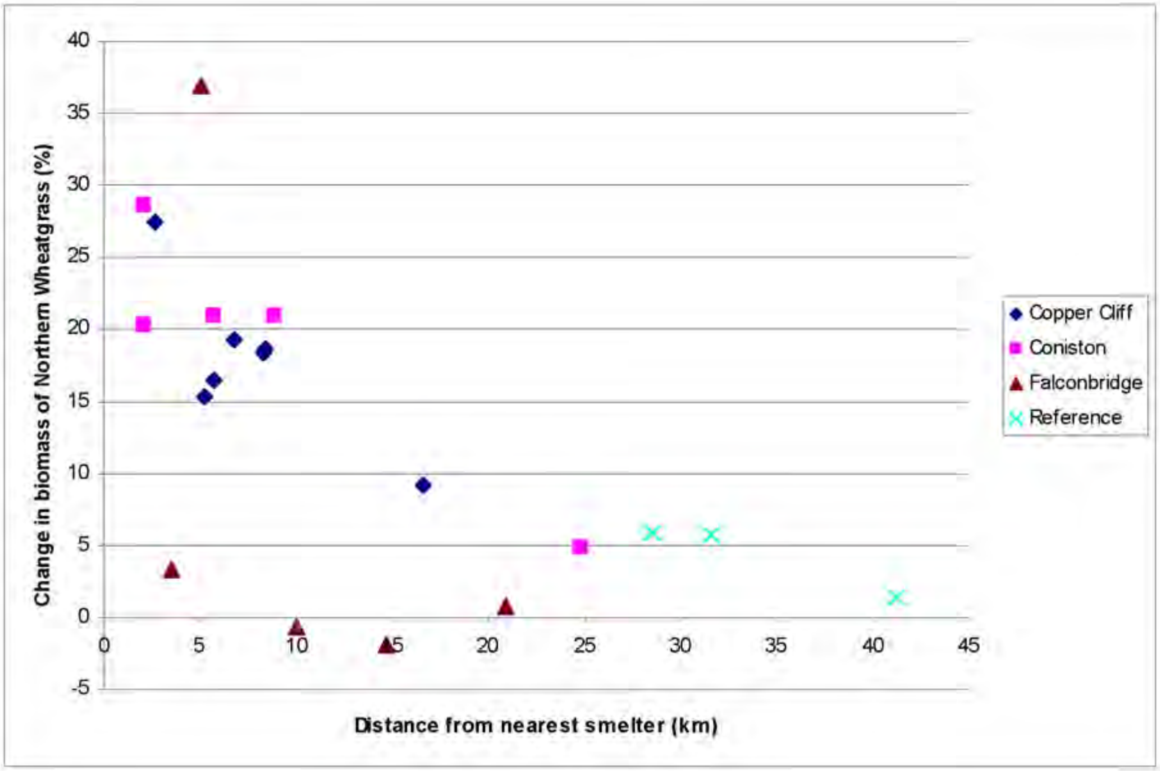


Figure 3-30c Change in biomass of Northern Wheatgrass following pH amendment.

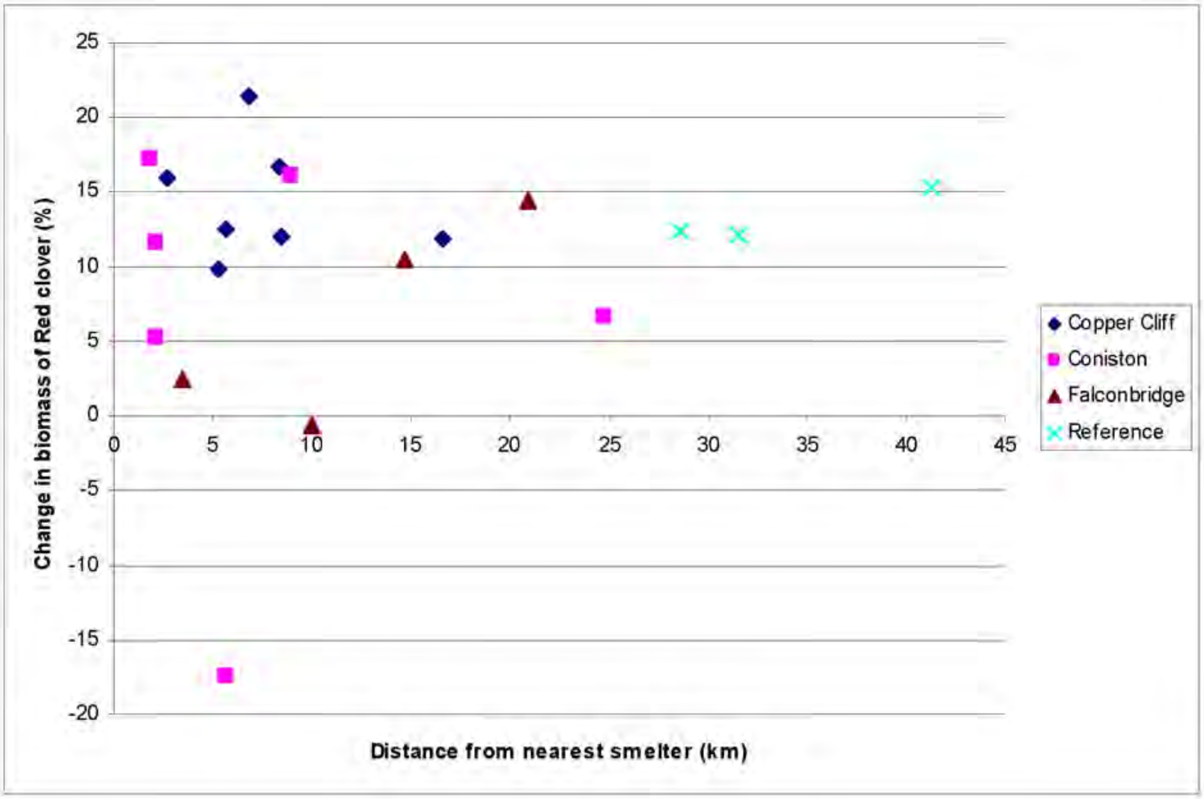


Figure 3-30d Change in biomass of Red Clover following pH amendment

Table 3.42a Emergence and Biomass for Red Clover and Northern Wheatgrass in Natural and pH-amended Soil for Coniston Sites

	Site	Mean emergence (%)			Mean biomass (mg)		
		Natural	pH-amended	% difference	Natural	pH-amended	% difference
Red Clover	CON-01	72	84	3.8	4.1	5.4	6.6
	CON-02	76	84	2.5	3.0	4.9	11.6
	CON-03	68	68	0	10.2	4.9	-17.4
	CON-05	68	72	1.4	2.5	4.8	16.1
	CON-06	65	92	8.6	2.8	5.8	17.2
	CON-08	64	88	7.9	2.5	3.1	5.2
Northern Wheatgrass	CON-01	88	100	3.2	8.4	10.2	4.8
	CON-02	84	84	0	2.7	10.1	28.6
	CON-03	100	64	-11	4.3	10.6	21.0
	CON-05	92	96	1.1	5.3	13.0	21.0
	CON-06	88	100	3.2	4.7	NA	NA
	CON-08	88	96	2.2	3.6	8.6	20.3

Table 3.42b Root Length and Weight Results for Red Clover and Northern Wheatgrass in Natural and pH-amended Soil for Coniston Sites

	Site	Mean Root Weight (mg)			Mean Root Length (mm)		
		Natural	pH-amended	% difference	Natural	pH-amended	% difference
Red Clover	CON-01	0.4	1.5	114	28.9	83.0	97
	CON-02	0.4	1.4	121	12.1	68.6	140
	CON-03	3.8	1.2	-106	34.5	60.2	54
	CON-05	0.4	1.0	90	10.2	50.5	133
	CON-06	0.4	1.4	109	9.5	53.7	140
	CON-08	0.4	0.4	-3	8.9	16.8	62
Northern Wheatgrass	CON-01	2.1	2.5	15	105.0	117.9	12
	CON-02	0.4	2.9	152	9.9	118.5	169
	CON-03	0.8	2.2	94	30.3	86.6	96
	CON-05	1.5	4.0	91	79.7	136.8	53
	CON-06	0.9	2.5	98	29.9	107.4	113
	CON-08	0.7	3.6	133	17.1	145.7	158

Table 3.42c Shoot Length and Weight Results for Red Clover and Northern Wheatgrass in Natural and pH-amended Soil for Coniston Sites

	Site	Mean Shoot Weight (mg)			Mean Shoot Length (mm)		
		Natural	pH-amended	% difference	Natural	pH-amended	% difference
Red Clover	CON-01	3.7	3.9	4	23.0	29.4	24
	CON-02	2.7	3.5	25	14.9	28.0	61
	CON-03	6.4	3.8	-52	17.2	31.1	57
	CON-05	2.1	3.8	58	12.8	24.4	63
	CON-06	2.4	4.4	58	11.4	24.2	72
	CON-08	2.1	2.7	25	16.0	19.9	22
Northern Wheatgrass	CON-01	6.2	7.7	21	103.7	122.0	16.2
	CON-02	2.4	7.2	102	57.4	117.4	68.7
	CON-03	3.5	8.4	81	71.5	123.9	53.6
	CON-05	3.8	9.0	81	81.5	120.1	38.3
	CON-06	3.9	5.2	28	79.4	91.5	14.2
	CON-08	2.9	5.0	53	61.9	100.3	47.4

Table 3.43a Emergence and Biomass for Red Clover and Northern Wheatgrass in Natural and pH-amended Soil for Copper Cliff Sites

	Site	Mean emergence (%)			Mean biomass (mg)		
		Natural	pH-amended	% difference	Natural	pH-amended	% difference
Red Clover	CC-01	56	96	13.2	4.1	6.2	9.8
	CC-02	72	80	2.6	3.7	6.2	12.5
	CC-03	52	92	13.9	4.6	8.9	15.9
	CC-04	72	96	7.1	2.9	7.2	21.4
	CC-06	72	88	5.0	4.4	7.2	12.0
	CC-07	64	80	5.6	3.7	7.4	16.7
	CC-08	92	88	-1.1	4.3	7.0	11.8
Northern Wheatgrass	CC-01	80	96	4.5	3.7	7.0	15.4
	CC-02	96	96	0.0	4.3	8.5	16.5
	CC-03	92	84	-2.3	3.1	10.6	27.5
	CC-04	72	96	7.1	3.8	8.5	19.2
	CC-06	88	81	-2.1	6.6	14.4	18.6
	CC-07	92	92	0	5.4	11.6	18.4
	CC-08	96	92	-1.1	6.2	9.0	9.2

Table 3.43b Root Length and Weight Results for Red Clover and Northern Wheatgrass in Natural and pH-amended Soil for Copper Cliff Sites

	Site	Mean Root Weight (mg)			Mean Root Length (mm)		
		Natural	pH-amended	% difference	Natural	pH-amended	% difference
Red Clover	CC-01	0.4	2.0	135	10.0	85.1	158
	CC-02	0.3	1.9	153	13.1	88.1	148
	CC-03	0.5	0.9	58	8.5	24.7	98
	CC-04	0.2	2.2	163	11.7	90.1	154
	CC-06	0.6	1.3	77	20.1	60.2	100
	CC-07	0.4	1.8	134	18.8	111.1	142
	CC-08	0.8	2.0	85	43.8	108.4	85
Northern Wheatgrass	CC-01	0.8	2.7	107	22.1	97.7	126
	CC-02	0.9	2.8	107	23.2	94.3	121
	CC-03	0.2	3.0	179	7.5	79.5	166
	CC-04	0.9	3.1	111	22.7	107.5	130
	CC-06	2.0	4.1	66	73.5	126.8	53
	CC-07	1.2	3.2	88	52.9	123.8	80
	CC-08	1.8	2.9	48	79.3	119.1	40

Table 3.43c Shoot Length and Weight Results for Red Clover and Northern Wheatgrass in Natural and pH-amended Soil for Copper Cliff Sites

	Site	Mean Shoot Weight (mg)			Mean Root Shength (mm)		
		Natural	pH-amended	% difference	Natural	pH-amended	% difference
Red Clover	CC-01	3.7	4.2	10	18.9	27.7	38
	CC-02	3.5	4.3	21	18.2	26.1	36
	CC-03	4.1	8.0	64	13.2	27.1	69
	CC-04	2.7	5.1	61	18.2	33.1	58
	CC-06	3.9	6.0	42	22.0	31.9	37
	CC-07	3.3	5.6	51	20.8	29.1	33
	CC-08	3.5	5.0	35	19.3	31.9	49
Northern Wheatgrass	CC-01	2.9	4.3	40	82.1	101.7	21.3
	CC-02	3.4	5.7	49	83.7	112.1	29.0
	CC-03	2.9	7.6	89	66.5	105.9	45.7
	CC-04	2.9	5.4	60	76.8	108.3	34.0
	CC-06	4.5	10.3	78	98.5	163.9	49.9
	CC-07	4.1	8.4	68	94.0	136.4	36.8
	CC-08	4.4	6.1	32	89.2	117.3	27.2

Table 3.44a Emergence and Biomass for Red Clover and Northern Wheatgrass in Natural and pH-amended Soil for Falconbridge Sites

	Site	Mean emergence (%)			Mean biomass (mg)		
		Natural	pH-amended	% difference	Natural	pH-amended	% difference
Red Clover	FB-01	nil	92	Na	n/a	5.5	n/a
	FB-02	84	80	-1.2	5.1	5.0	-0.6
	FB-03	76	80	1.3	3.5	6.3	14.4
	FB-05	80	88	2.4	6.3	6.9	2.4
	FB-06	84	88	1.2	4.7	7.1	10.4
Northern Wheatgrass	FB-01	52	96	14.9	1.7	11.3	36.9
	FB-02	100	92	-2.1	6.7	6.5	-0.6
	FB-03	96	96	0.0	7.5	7.7	0.8
	FB-05	96	100	1.0	7.7	8.7	3.3
	FB-06	96	92	-1.1	8.5	7.9	-1.9

Table 3.44b Root Length and Weight Results for Red Clover and Northern Wheatgrass in Natural and pH-amended Soil for Falconbridge Sites

	Site	Mean Root Weight (mg)			Mean Root Length (mm)		
		Natural	pH-amended	% difference	Natural	pH-amended	% difference
Red Clover	FB-01	No plants	1.6	na	No plants	95.1	na
	FB-02	0.4	0.4	4	39.9	60.8	43
	FB-03	0.3	2.2	152	8.0	112.8	174
	FB-05	1.2	2.0	50	52.4	97.8	60
	FB-06	0.8	2.2	90	51.1	103.4	68
Northern Wheatgrass	FB-01	0.5	3.5	147	20.7	127.7	144
	FB-02	0.9	1.4	40	79.8	96.3	19
	FB-03	2.3	2.8	21	97.6	135.1	32
	FB-05	2.2	3.6	49	90.7	161.3	56
	FB-06	3.0	2.9	-4	147.1	124.3	-17

Table 3.44c Shoot Length and Weight Results for Red Clover and Northern Wheatgrass in Natural and pH-amended Soil for Falconbridge Sites

	Site	Mean Shoot Weight (mg)			Mean Shoot Length (mm)		
		Natural	pH-amended	% difference	Natural	pH-amended	% difference
Red Clover	FB-01	No plants	3.9	na	No plants	30.6	na
	FB-02	4.7	4.5	-2.9	20.3	25.1	21
	FB-03	3.2	4.1	25.1	12.8	29.1	78
	FB-05	5.1	5.0	-2.9	25.3	31.8	23
	FB-06	3.9	5.0	25.3	19.5	33.0	51
Northern Wheatgrass	FB-01	1.2	7.8	148	43.9	124.4	95.7
	FB-02	5.8	5.2	-12	104.5	96.3	-8.2
	FB-03	5.2	4.9	-6	84.5	93.0	9.6
	FB-05	5.5	5.1	-7	90.1	99.7	10.1
	FB-06	5.5	5.0	-10	104.3	92.0	-12.6

Table 3.45a Emergence and Biomass for Red Clover and Northern Wheatgrass in Natural and pH-amended Soil from the Reference Sites

	Site	Mean emergence (%)			Mean biomass (mg)		
		Natural	pH-amended	% difference	Natural	pH-amended	% difference
Red Clover	REF-02	84	96	3.3	5.4	8.8	12.1
	REF-03	100	80	-5.6	2.4	4.5	15.3
	REF-04	72	76	1.4	4.0	6.7	12.3
Northern Wheatgrass	REF-02	80	84	1.2	7.9	9.9	5.7
	REF-03	92	96	1.1	10.0	10.5	1.4
	REF-04	96	88	-2.2	6.7	8.5	5.9

Table 3.45b Root Length and Weight Results for Red Clover and Northern Wheatgrass in Natural and pH-amended Soil for Reference Sites

	Site	Mean Root Weight (mg)			Mean Root Length (mm)		
		Natural	pH-amended	% difference	Natural	pH-amended	% difference
Red Clover	REF-02	1.1	3.0	93	64.0	115.3	57
	REF-03	0.4	1.4	105	104.5	75.9	-32
	REF-04	0.7	2.2	103	22.9	109.6	131
Northern Wheatgrass	REF-02	2.3	3.6	43	87.8	140.5	46
	REF-03	4.2	4.1	-2	145.0	130.7	-10
	REF-04	2.5	3.4	30	109.6	140.0	24

Table 3.45c Shoot Length and Weight Results for Red Clover and Northern Wheatgrass in Natural and pH-amended Soil for reference Sites

	Site	Mean Shoot Weight (mg)			Mean Shoot Length (mm)		
		Natural	pH-amended	% difference	Natural	pH-amended	% difference
Red Clover	REF-02	4.2	5.8	30.3	19.7	30.3	43
	REF-03	2.0	3.1	45.7	24.7	26.5	7
	REF-04	3.3	4.5	29.2	13.9	26.6	63
Northern Wheatgrass	REF-02	5.6	6.4	13	111.1	122.9	10.1
	REF-03	5.8	6.4	11	106.9	107.6	0.6
	REF-04	4.2	5.1	20	86.5	97.2	11.7

Raising the pH of the soil often reduced the toxicity of the soil, but did not alleviate it altogether. With few exceptions, pH amendment resulted in an increase in emergence and biomass for both northern wheatgrass and red clover. Soil amendment generally had less of an effect on plant growth in soils from the Reference sites.

In general, the improvement in plant performance (emergence and biomass in both species) following pH-amendment was greater in soils from sites close to the smelters than in soils further away from the smelters or from the reference sites. Plant response was most pronounced in soil from FB-01, which had the lowest pH as well as the highest total metal levels measured at any site along this transect (Cu = 909 mg/kg and Ni = 535 mg/kg).

3.14.2 The Effect of Historic Liming and Re-greening: A Comparison of CON-07 and CON-08

The impact to vegetation in the Sudbury region has been examined in great detail over the past three decades. Winterhalder (1996, 1983) and Courtin (1994) documented that the natural reestablishment of vegetation in the Sudbury area since the decrease in emissions has been hindered by metals and acidic soil conditions as well as numerous other factors such as foliar damage from fumigations, reductions in seed production and seed viability, low germination success, poor root development, drought and poor anchoring of seedlings in the frost (needle-ice) susceptible soils and soil loss from erosion.

The term “re-greening” was coined to describe the reclamation activities that have re-established forest and vegetation cover on industrially damaged land in the Sudbury region. The mining companies (Vale

Inco and Xstrata Nickel.) expanded their reclamation activities in the 1960s in response to increased public concern about the environment. In May 1978, community initiatives evolved into one of the largest documented community-based reclamation programs for industrially disturbed lands: the City of Sudbury's Land Reclamation Program. Studies in the 1970s indicated that liming of the soil raised pH sufficiently to reduce soil toxicity, facilitating growth and survival of grasses on many test sites throughout the city. The re-greening program was established and aimed to reduce dust, add colour to the blackened landscape by establishing a conifer and mixed hardwood tree cover and provide areas for recreation. Between 1978 and 1983 residents were employed by the Regional Municipality of Sudbury to manually apply lime, fertilizer and seed on sites selected along the major arteries into Sudbury, and to carry out complementary reclamation activities. By the end of 2005, approximately 3,367 ha of land had been treated by the Land Reclamation Program. While past re-greening initiatives focused on aesthetic improvements, recent efforts have turned toward considering ecological objectives creating self-sustaining plant communities that more closely resemble pre-mining forest communities. A review of the past and present re-greening efforts in the Sudbury region is presented in Volume I, Chapter 4.

Dolomitic limestone (calcium and magnesium carbonate) was used to reduce soil acidity on chosen lands. The limed areas were then hand-fertilized with a fertilizer high in phosphorus (6-24-24) to promote grass germination and growth. The direct effect of liming was to change soil pH but this indirectly changed a multitude of properties that vary with pH (Troeh and Thompson, 2005).

"Re-greening" activities were conducted at CON-07 following the standard protocols of the City of Sudbury Land Reclamation Program, as advised by the Vegetation Enhancement Technical Advisory Committee (VETAC). From 1978 to 1984, CON-07 was treated through liming, fertilizing, and grassing. In an effort to reduce soil acidity, dolomitic limestone was applied on the site at a concentration of 10 tonnes per hectare. Fertilizer (Type 5-20-20) containing 5% nitrogen, 8.7% elemental phosphorus, and 16.6% elemental potassium was applied on the site at a concentration of 40 kg per hectare. The high amount of phosphorus in the fertilizer was necessary for promoting grass germination and growth. The site was then seeded (40 kg seeds/ha) with a seed mixture comprised of 80% grasses and 20% legumes. Grass seed types included Red Top (*Agrostis gigantean*), Red Fescue (*Festuca rubra*), Timothy (*Phleum pratense*), Canada Blue Grass (*Poa compressa*), and Kentucky Blue Grass (*Poa pratensis*). The legumes mixture included Bird's foot Trefoil (*Lotus corniculatus*) and Alsike Clover (*Trifolium hybridum*). In 1986, 1995, and 1997, the second stage of the Land Reclamation Program was carried out at CON-07. Three major species of trees were planted throughout the site during these three years, Jack Pine (*Pinus* *banksiana*), Red Pine (*Pinus resinoasa*), and White Pine (*Pinus strobus*). A small number of Red Oak (*Quercus rubra*) was also planted in 1986. All planted trees were obtained from local nurseries.

During the Objective #1 studies, identical information was collected at both CON-07 and CON-08. Obviously the limed site, CON-07, is quite different from the 18 test sites but its existence and proximity to CON-08 provide a unique opportunity to evaluate the efficacy of historic liming and replanting. CON-07, the limed site, is included in all assessment reports but has not been considered in the final ranking of the sites.

The objective of this section is to compare the results from the individual LOE for CON-07 and CON-08. This comparison will give an indication of the effect of the historic pH-amendment (liming) and replanting, assuming other site conditions are similar given their close proximity to each other.

3.14.2.1 COC Concentrations

A comprehensive table showing the concentrations of all measured metals at the test, limed and reference sites is provided in Appendix GD6-1 (total nitric acid extractable metals in 0-5 cm cores), GD6-2 (water leach metals in 0-5 cm cores). The nitric acid extractable and water leach concentrations of COC in the 0-5 cm core samples from CON-07 and CON-08 are shown in Table 3.47. Total and water extractable copper and nickel, were elevated at both CON-07 and CON-08 compared to the concentrations measured at the three reference sites (Table 3-46).

Table 3.46 Total (HNO_3) and Water Leach Concentrations of COC in 0-5 cm Core Samples

Metal	CON-07 Total (mg/kg)	CON-08 Total (mg/kg)	CON-07 Water Leach (mg/kg)	CON-08 Water Leach (mg/kg)
Arsenic	7.2	5.2	0.09	0.04
Cadmium	0.15	0.15	<DL	<DL
Cobalt	10.2	10.9	0.08	0.08
Copper	240	107	1.73	0.38
Lead	11	9.1	0.07	<DL
Nickel	255	132	1.76	2.55
Selenium	1.1	0.89	<DL	<DL

<DL indicates concentration was less than the method detection limit

The total COC concentrations of As, Cd, Co, Pb and Se at CON-07 and CON-08 were quite low and well below MOE Table A guidance levels. The most striking difference between the two sites was in the concentrations of copper and nickel, which were 77% and 64%, respectively, higher at CON-07. This may be reflective of the highly eroded state of CON-08. This pattern was also generally reflective of the water leach metal concentrations, except for Ni, where the water leach concentration was 37% higher at CON-08 as compared to CON-07 (CON-08 Ni 1.76 mg/kg; CON-08 Ni 2.55 mg/kg).

3.14.2.2 Plant Community LOE

The plant community assessment provided a detailed snapshot of the vegetation community at each site during the summers of 2004 and 2005. At each site, observational data were collected as part of five major ecological components: a broad plant inventory, percent cover assessment, detailed tree and tall shrub assessment, assessment of coarse woody debris and an ecosite classification. The Plant Community Assessment is described in greater detail in Section 3.6. The field methodology protocol is presented in Appendix GB6. The raw data used in the evaluation and ranking of the sites are provided in Appendix GE2. The raw data were interpreted and placed into one of four ecological criteria: site biodiversity, ecological integrity, long-term site productivity and soil and water conservation. These criteria were composed of various indicators. The application of rankings followed a step-wise process that is presented in the ranking report in Appendix GE-4. The comparison of the plant community at CON-07 and the adjacent unlimed site, CON-08, is discussed in the following section.

The comparison of the plant communities at CON-07 and CON-08 revealed very different structures (Table 3-47). Although the sites are adjacent to each other (the centre stakes being less than 500 m apart), the two communities displayed completely different characteristics (Figure 3-31). CON-07 represented a site that had a plant community in transition, while CON-08 showed clear indications of being impacted.

Table 3.47 Summary of Plant Community Indicators – CON-07 and CON-08

	CON-07*	CON-08
Soil Biodiversity		
Species Richness (total species)	80	41
Species Diversity (H' value- all species)	1.59	1.2
Species Dominance (% cover)	22.44	25.68
Degree of Disturbance (proximity to barren and semi-barren areas)	High	High
Life History (% perennial species)	82.76	100
Plant Community Structure (# of strata)	5	5
Downed Woody Debris (count)	0	0

Table 3.47 Summary of Plant Community Indicators – CON-07 and CON-08

	CON-07*	**CON-08**
Degree of Regreening Intervention (proximity to disturbed and regreened areas)	High	High
Ecological Integrity		
Life Form of Trees (% cover-canopy/% cover-understory)	0/2.25	0/2.25
Introduced or Invasive (% non-native and potentially invasive species)	55.68	16.72
Successional Stage - shade tolerant (# indicator species)	6	1
Substrate (% total mineral substrate)	6.92	20.48
Regeneration (% seedlings, saplings/% tree species in understory)	4.74/33.5	2.04/2.25
Reestablishment of Sensitive Species (# good/# intermediate/# poor indicators)	6/10/4	2/7/5
Species Richness (total species)	80	41
Presence of Metal or Acid Tolerant Species (# of indicators)	12	14
Long Term Site Productivity		
Pernent Mortality and Dieback of Tree Species (% overall dieback)	12.5	No trees present
Tree Height (m)	6	No trees present
Tree/Tall Shrub Density (# per hectare)	6700	1500
Presence of Aspen or Poplar on site (height-canopy/height-understory/# trees in canopy/# trees in understory)	6.2/1.2/39/34	No trees present
Volume of Downed Woody Debris (average volume)	0	0
Length of Downed Woody Debris (average length)	0	0
Range of Decomposition (# classes represented)	0	0
Soil and Water Conservation		
Tree and Tall Shrub Density (# per hectare)	5650	0
Percent Plant Cover (surface soil retention index)	100	81.66
Percent Leaf Litter Cover (%)	76.24	3.76
Percent Slope (%)	<5	10
Soil Texture	Silt Loam	Silt Loam

*CON-07 is the historically limed and re-greened site
See Appendix GE-4 for full explanation and interpretation of Indicators

The plant community at CON-07 was dominated by scattered, stunted poplar trees and a continuous cover of herbaceous species. The species diversity at the site was comparable to, or higher than, reference site values for all indices. The site biodiversity, ecological integrity and long-term productivity were all ranked as moderately impacted but the soil and water conservation of the site was deemed good. Conifer cover was virtually absent in the community despite the planting of white and jack pine 10 to 20 years ago. This lack of species represents a gap in the ecological integrity of the site as the conifers would provide no protective winter covering to ameliorate the site from high winds and cold temperatures. In addition, there were a very large number of non-native species, accounting for over half of the ground cover at this site, which is indicative of the history of liming and seeding on this site. A high number of metal and acid tolerant species as well as cryptogam indicator species (indicative of improved site conditions) were recorded at this site. There was good evidence of successful regeneration of white birch, balsam poplar and trembling aspen in the understory.

There was only limited evidence of dieback at the site. Not surprisingly, maximum tree height at this site was low and downed woody debris (DWD) was absent at this site. This represents another gap in the ecosystem, whereby long-term site productivity is potentially in jeopardy due to the lack of an adequate supply of organic material to the soil. However, trembling aspen and balsam poplar were abundant at the site, suggesting that this was a relatively productive site. The high tree density values also support this interpretation. The silt loam-textured soils consisted of highly erosion- and frost-prone silts and clays. However, the level terrain, continuous plant cover and high density of trees greater than 1 m in height minimized the risk of rapid soil water/soil solution flow-through in the silt loam soils. During the soil collection phase of the project, the field workers discovered earthworms at this site. No attempt was made to identify which species they were but it was clear that a thriving and successful earthworm population existed.

In contrast, CON-08 displayed many of the characteristics of a stressed plant community. The site biodiversity, ecological integrity, site productivity and soil and water conservation were all ranked severely impacted and at risk. The analysis showed low species richness and species diversity. Downed woody debris, trees and tall shrubs were completely absent, representing a major gap in the biodiversity of the site. This gap would leave the site vulnerable to the loss of surface soils due to erosion and to losses in soil quality due to the very limited seasonal additions of organic matter. The plant community structure was characterized by few species within each layer and the complete absence of trees. Conifer cover was negligible, and there was a scarcity of shade tolerant indicator species and cryptogam, indicators of improved site conditions. In addition, there were high numbers of metal and acid tolerant species and very little evidence of regeneration. Of major concern was that over 20% of the surface was exposed, unproductive mineral substrate. As a result, the risk of soil loss through surface erosion remained high and subsoil water retention would be limited due to the absence of a shrub and tree cover. The site displayed strong evidence of surface soil disturbances. In contrast to CON-07, only 500 m away, no earthworms were found at this site.

Figure 3-31 Photographs of: a) The Historically Limed and Re-greened Site, CON-07; and, b) CON-08

3.14.2.3 Toxicity Testing LOE

The methods, analysis and results generated from the toxicity tests in natural site soil were presented in Section 3.7. The results of the soil toxicity are presented in the “Toxicity Testing LOE Ranking Report” located in Appendix GF-9, and summarized in Section 3.8. Plant tissue has been retained to permit analysis of the samples in the future by interested parties. The following section compares the toxicity test results of CON-07 and CON-08.

A summary of the toxicity test results in the historically limed soil from CON-07 and natural site soil from CON-08 is shown in Table 3.48. CON-08 was found to have a soil pH of 4.45, while the soil pH of CON-07 was 7.21. As a result, all of the toxicity test plant species performed better in CON-07 than at CON-08. For instance, the performance of goldenrod was up to 181% higher at CON-07 (mean root length= 78.5 mm; mean shoot length= 4.0 mm). This was also the case for red clover, which demonstrated an increase in growth of up to 144% at CON-07 relative to CON-08. Root and shoot length for white spruce increased up to 144% at CON-07 compared to CON-08. Root and shoot length of northern wheatgrass was also up to 137% higher at CON-07 relative to CON-08.

Table 3.48 Toxicity Test Results in Natural Site Soils from CON-07 (pH= 7.21) and CON-08 (pH=4.45)

Species	Measurement Endpoint	CON-07 (Historically limed)	CON-08 (Natural)	Percent Difference (%)
Goldenrod	Mean Root Length (mm)	78.5	4.0	181
	Mean Shoot Length (mm)	30.8	4.0	154
	Mean Root Weight (mg)	1.1	1.1	0
	Mean Shoot Weight (mg)	11.3	2.1	137
White Spruce	Mean Root Length (mm)	56.1	9.1	144
	Mean Shoot Length (mm)	31.7	23.7	29
	Mean Root Weight (mg)	0.9	0.4	77
	Mean Shoot Weight (mg)	3.9	2.6	40
Red Clover	Mean Root Length (mm)	54.7	8.9	144
	Mean Shoot Length (mm)	28.8	16.0	57
	Mean Root Weight (mg)	1.4	0.4	111
	Mean Shoot Weight (mg)	4.4	2.1	71
Northern Wheatgrass	Mean Root Length (mm)	92.3	17.1	137
	Mean Shoot Length (mm)	90.9	61.9	38
	Mean Root Weight (mg)	2.0	0.7	96
	Mean Shoot Weight (mg)	5.0	2.9	53

To investigate the influence of pH on plant growth, site soil from CON-08 was amended with calcium carbonate to raise the pH from 4.4 to 5.2 ± 0.2. The toxicity of the pH-amended soil was examined using red clover, northern wheatgrass and earthworms. Table 3.48 provides the results of the two soil conditions (natural and pH-amended) for the CON-08 toxicity tests.

The data in Table 3.49 show that raising the soil pH significantly affected test results for northern wheatgrass, but less so for red clover. The growth of northern wheatgrass in the pH-amended CON-08 soils also exceeded growth in the CON-07 natural soils; but red clover did not perform as well.

Table 3.49 Toxicity Test Results in Natural Site Soil and pH-amended Soil from CON-08

Species	Measurement Endpoint	CON-08 (Natural)	CON-08 (pH-amended)	Percent difference (%)
Red Clover	Mean Root Length (mm)	8.9	16.8	61
	Mean Shoot Length (mm)	16.0	19.9	22
	Mean Root Weight (mg)	0.4	0.4	0
	Mean Shoot Weight (mg)	2.1	2.7	25
Northern Wheatgrass	Mean Root Length (mm)	17.1	145.7	157
	Mean Shoot Length (mm)	61.9	100.3	47
	Mean Root Weight (mg)	0.7	3.6	135
	Mean Shoot Weight (mg)	2.9	5.0	53

Toxicity test results for earthworms in site soils at CON-07 and pH-amended soils at CON-08 are shown in Table 3.50. Although survival rates for adult earthworms were quite high in the CON-08 pH-amended soil, the earthworms were unable to successfully reproduce. Thirty percent of the earthworms in the CON-08 pH-amended soil were missing their reproductive organs midway through the 63-day reproduction test. Earthworm survival rates are a very insensitive measure of overall health. Earthworms are resilient and will live in all types of conditions. However, they will only reproduce in good conditions. The earthworms from the CON-07 site test were healthy, and were able to successfully reproduce.

Table 3.50 Toxicity Test Results for Earthworms in Site Soils from CON-07 (pH= 7.21) and pH-amended Soils from CON-08 (pH= 0.2 + 5.2)

Species	Measurement Endpoint	CON-07	CON-08 amended	% Difference
Earthworms	Adult Survival (35 d)	95%	100%	5
	Mean Juvenile Weight (mg)	2.4	No juveniles	NA
	Number of Juveniles	1.8	No juveniles	NA

In summary, it is evident that all test species in natural soil performed better at CON-07 than at CON-08. When the pH at CON-08 was raised, the plant growth for northern wheatgrass improved beyond the performance at CON-07. Alternatively, for red clover, plant growth did improve but not to the same extent. Earthworms were sensitive to CON-08 soil and did not reproduce in the natural or pH-amended soil from this site.

Toxicity test rankings for CON-07 and CON-08 are presented in Table 3.51. The results illustrate that test species performed better in the natural CON-07 soils compared to the natural soil at CON-08. Raising the soil pH in CON-08 soil greatly improved test performance for northern wheatgrass but less so for red clover.

The toxicity testing results suggest that pH is not the only factor limiting plant growth in this area. They also suggest that liming or pH amendment affects plant species differently, which is an important consideration for future re-greening and planting strategies.

Table 3.51 Comparison of Toxicity Testing Results for CON-07 Soils and Natural and pH-amended Soils from CON-08

Indicator	CON-07 (limed site)		CON-08 (natural)		CON-08 (pH-amended)	
	Approach 1	Approach 2	Approach 1	Approach 2	Approach 1	Approach 2
Northern Wheatgrass	Yellow	Yellow	Red	Red	Green	Green
Red Clover	Green	Green	Yellow	Red	Red	Red
White Spruce	Yellow	Red	Red	Red	N/A	N/A
Goldenrod	Green	Yellow	Yellow	Red	N/A	N/A
Earthworms	Red	Red	N/A	N/A	Red	Red

*N/A indicates that test was not run at these sites

3.14.2.4 Soil Characterization LOE

The methods and results from the soil collection and analysis were presented in Section 3.4. The ranking of the soil physical and chemical characteristics is presented in detail in the "Soil Characterization LOE Ranking Report" located in Appendix GD-9-2 and is summarized in Section 3.5. The results of the physical and chemical analysis of the soil are presented in Appendix GD and a summary of the most relevant values at CON-07 and CON-08 are presented in Table 3.52. In the following section various physical and chemical characteristics of CON-07 and CON-08 are compared.

In terms of particle size, the soil from CON-07 and CON-08 (see Table GD5-2.1 in Appendix GD-5) is quite similar; both are silt loams with bulk density values in the same range (CON-07 1.33 g/cm^3; CON-08 1.32 g/cm^3). In terms of soil development, definite differences were apparent. At CON-07, the soil is imperfectly drained and there is evidence of moderate erosion. However, the relict subsurface mineral soil horizons were well developed and a thin Ah horizon, the product of cultivation and organism activity, was present at the site. At CON-08 the imperfectly drained soil was highly eroded and it was evident that the LFH horizon was inadequate for seedling germination and growth. The surface mineral horizons (Ae) were also completely eroded from the site with the structural integrity of the remaining mineral horizons at this site being very poor.

Table 3.52 Summary of Physical and Chemical Parameters- CON-07 and CON-08 Site Soils

	CON-07*	CON-08
Soil Properties		
Particle Size	Silt loam	Silt loam
Bulk Density (g/cm^3)	1.33	1.32
Soil pH (water/slurry in cores)	7.19	4.5
Organic Matter (%)		
Total Nitrogen	0.1	0.03
Organic Carbon	1.7	0.82
Soil Exchange Complex Chemistry		
Cation Exchange (cmol(+)/kg)	15	11
Calcium (cmol(+)/kg)	9	0.82
Magnesium (cmol(+)/kg)	1	1
Ca:Mg Ratio	7	0.8
Fertility Parameters (mg/kg)		
N as Ammonium	0.68	0.01
Extractable P	7	42
Extractable K	68	64
Extractable Fe	321	547
Extractable Mn	38	28
Extractable Mg	227	14

Comparisons of the chemical properties of the two adjacent sites reveal numerous differences that are likely affecting the recovery of the forested community. The historic liming and re-greening activities at CON-07 resulted in the pH of the soil being significantly (almost 50%) higher (Table 3.51). Low soil pH can cause lower soil fertility and a less than ideal medium for the growth of plants (Troeh and Thompson, 2005).

Both of the sites are lacking organic matter, as measured by the total nitrogen (CON-07 0.1% and CON-08 0.03%) and organic carbon levels (CON-07 1.7% and CON-08 0.82%) when compared to the ranges measured at the reference sites (see table GD9-2-4.1, total nitrogen range 0.23-0.34% organic carbon 4.18-6.93% in Appendix GD-9). Ashman and Puri (2002) describe low soil carbon and nitrogen levels as being less than 2 and 0.1% respectively. These measurements further indicate that both sites can be considered lacking in organic matter. Along the Coniston transect, the majority of sites were found to be highly eroded and lacking in organic matter. However, the levels at CON-08 seemed to be at the lower end of the spectrum signalling the highly impacted nature of the soil.

The cation exchange capacity of the two sites were similar (CON-07 15 cmol(+)/kg and CON-08 11 cmol(+)/kg) although these sites are much lower than the reference site CEC values (CEC range 27 - 29 cmol(+)/kg). The calcium levels at CON-07 (9 cmol(+)/kg) were 167% higher than at CON-08 (0.82 cmol(+)/kg) and much higher than at any of the reference sites (range 0.38 - 2.8 cmol(+)/kg), reflecting the past liming activities that have occurred. Exchangeable calcium in soil has an important relationship to soil pH and the availability of several macro- and micronutrients. Calcium is a structural component of plant cell walls and is, therefore, vital in the formation plant growth (Troeh and Thompson, 2005). Plants that are grown in Ca deficient soil will often be stunted which was observed in the plant community at CON-08.

Soils rarely contain enough nitrogen for maximum plant growth. Generally younger plants need more nitrogen than older plants. Organic matter, which contains nitrogen, must be at least partially decomposed before the nitrogen is available. Microbial action gradually decomposes the organic matter producing the ammonium ion, a form of nitrogen that is readily assimilated by plants. The available nitrogen as ammonium at CON-07 (0.68 mg/kg) is comparable to the level found at some of the reference sites (0.45-3.49 mg/kg) but nearly 200% higher than the level found at CON-08 (0.01 mg/kg).

Magnesium is contained in dolomitic limestone, the liming application applied to CON-07. It is not surprising, therefore, to find that the extractable Mg levels were almost 16 times higher at the limed site than the unlimed site (Table 3.52). Mg is vital to the process of photosynthesis as it is a component of chlorophyll (Troeh and Thompson, 2005).

The iron levels at both the limed and unlimed sites were relatively low (CON-07, 321 mg/kg; CON-08, 547 mg/kg) when compared to the reference sites (918 - 1256 mg/kg). However, the levels at the unlimed site (CON-08) were about 50% higher than at CON-07. Iron is an abundant essential element and is often present in soils at high concentrations but it is also one of the most commonly deficient micronutrients, due to the extremely insoluble nature of certain ferric compounds (Troeh and Thompson, 2005). At low pH, such as those found in the Sudbury regions (4-5), these compounds become more available and iron often becomes toxic.

In summary, soil chemistry (irrespective of metal levels) was different between the two sites. The effect of past liming activities was still apparent and contributed to better growing conditions at CON-07 as compared to the unlimed site (CON-08).

3.14.2.5 Decomposition LOE

Decomposition is a vital function in a forest ecosystem. The process of litter decomposition is critical for maintaining site fertility and productivity by returning nutrients to the soil where they become available to plants. To measure decomposition, a year-long study was initiated with the objective to measure the mass loss of leaf litter, in *in-situ* litter bags containing white birch (*Betula papyrifera*). The methods used to construct, place and analyze the litter bags are presented in Appendix GB Protocol 9, and are discussed in the Decomposition LOE Ranking Report presented in Appendix GG4. Section 3.10 presents a summary of these reports.

Decomposition, as measured by mass loss, was evaluated and ranked by comparing the decomposition rate at each site to the calculated mean rate of the three reference sites (REF_{mean}). This comparison provided a measure of the ability of the site microorganisms to decompose organic matter. Decomposition at CON-07 and CON-08 is compared and discussed below.

At the limed site (CON-07) 53% of the mass of the leaves was lost over the course of the 13-month study whereas, at the unlimed site only 35% of the mass of the leaves decomposed. This resulted in a mass loss at CON-07 that was 40% greater than at CON-08.

The rate of decomposition (k) per year was calculated as 0.55 g/g/year (dry weight) at CON-07 and 0.26 g/g/year (dry weight) at CON-08. When compared to REF_{mean} the rate of decomposition at both CON-07 and CON-08 was significantly lower, indicating a severely impacted microorganism system that could potentially lead to increasingly larger differences in mass lost over time.

3.14.2.6 Bioavailability

The bioavailability of Cu and Ni in the homogenized soil samples collected at CON-07 (limed) and CON-08 (not limed) was examined by comparing the results of the various extraction methods undertaken at McGill University. The methods used and results of this analysis are provided in detail in Section 3.15. The McGill team used four extraction methods of differing strength. The methods in order from strongest to weakest were: HNO_3; EDTA; $CaCl_2$ and column leach. The results of each method yield a metal concentration that is reported to be indicative of differing metal fractions within the sample. The merits of each method are discussed in section 3.15.1 but briefly: HNO_3 method obtains “total” metal levels of the sample, EDTA gives a measure “fixed” metal levels, $CaCl_2$ provides a measure of phytoavailable metals and, the column leach gives a measure of soluble trace metals.

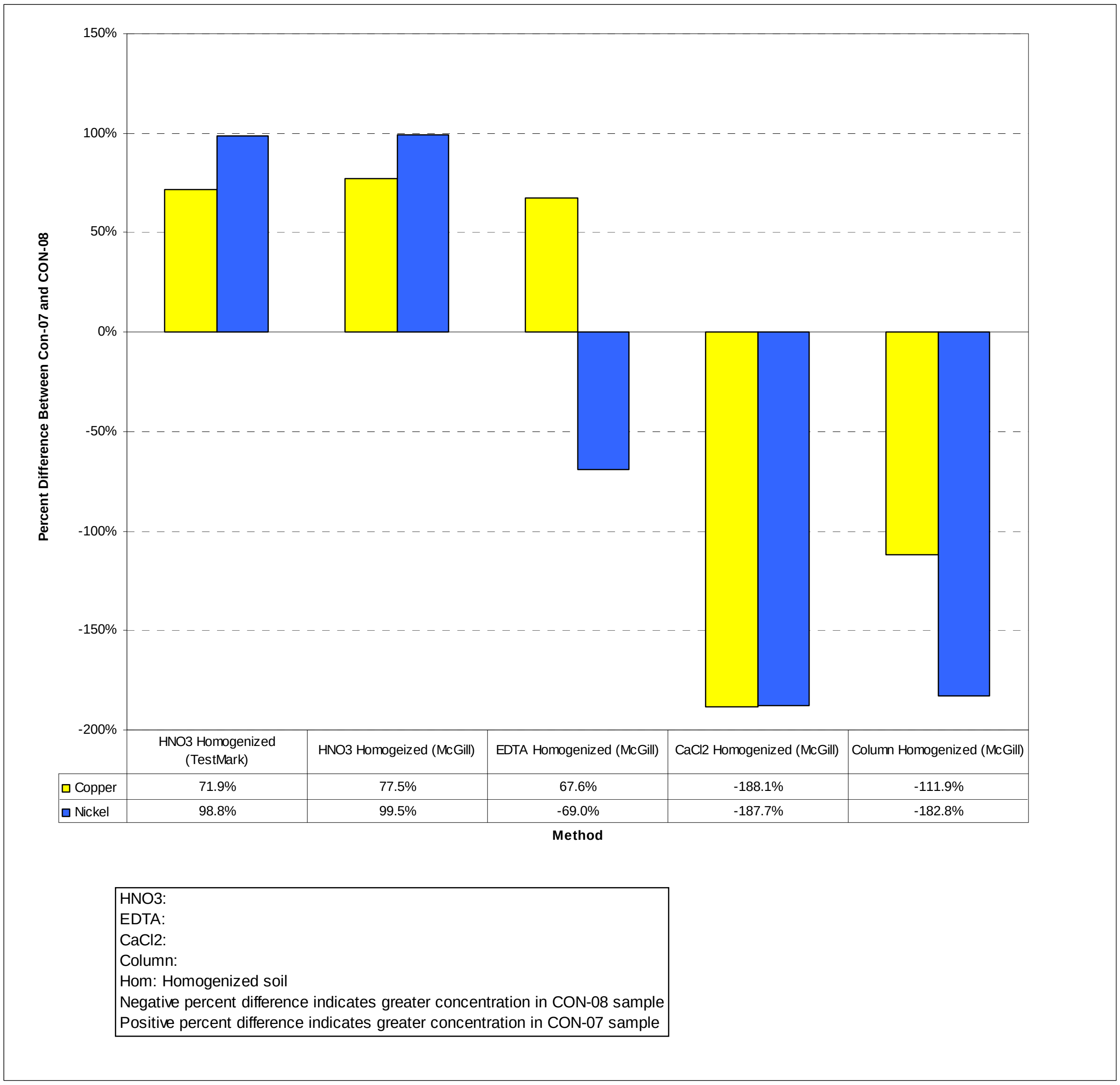
Table 3-53 provides the Cu and Ni levels at CON-07 and CON-08 obtained by these various methods. For comparative purposes the HNO$_3$ and Water Leach levels in the homogenized soil and core samples obtained by Testmark Laboratories are also provided. The HNO$_3$ extracted Cu and Ni levels obtained by Testmark laboratory and at McGill are comparable with less than a 20% difference. These results indicate that the HNO$_3$ methods used by the two laboratories yield comparable results.

Table 3.53 Copper and nickel concentrations in core and homogenized soil samples from CON-07 and CON-08, as measured by various extractions

		Copper		**Nickel**	
		CON-7	**CON-08**	**CON-07**	**CON-08**
Core Samples	Water Leach (µg/L)^a	1.73	0.38	1.76	2.55
	HNO3 (mg/kg)^a	240	107	255	132
Homogenized Samples	HNO3 (mg/kg)^a	170	80.1	313	106
	HNO3 (mg/kg)^b	154	68	280	94
	EDTA (mg/kg)^b	39.26	19.42	17.52	35.96
	CaCl2 (mg/kg)^b	0.16	5.29	0.82	26.01
	Column (L/kg)^b	0.0063	0.0223	0.0120	0.2668

a Analysis conducted by Testmark
b Analysis conducted at McGill University

The percent difference between the metal levels at CON-07 and CON-08 were calculated and are displayed graphically in Figure 3-32. In the figure a negative percent difference (bars of the graph are below the 0% axis line) indicates that the concentration of metal in the sample is greater in the CON-08 sample than the CON-07 sample. The reverse is true for a positive percent difference (bars of the graph are above the 0% axis line) where the concentration of metal in the CON-07 sample is greater than the CON-08 sample.



	HNO3 Homogenized (TestMark)	HNO3 Homogeized (McGill)	EDTA Homogenized (McGill)	CaCl2 Homogenized (McGill)	Column Homogenized (McGill)
🟨 Copper	71.9%	77.5%	67.6%	-188.1%	-111.9%
🟦 Nickel	98.8%	99.5%	-69.0%	-187.7%	-182.8%

HNO3:
EDTA:
CaCl2:
Column:
Hom: Homogenized soil
Negative percent difference indicates greater concentration in CON-08 sample
Positive percent difference indicates greater concentration in CON-07 sample

Figure 3-32 Percent differences in metal concentrations, as measured by various extractions, between CON-07 and CON-08

These results indicate that:

- The HNO_3 (total) Cu and Ni levels are 72% and 99% higher at the limed site CON-07 than they are at CON-08. The result confirms the findings in the core samples.
- Using the slightly weaker extraction method of EDTA the Cu level obtained at CON-07 is higher (67%) than the level found at CON-08. This trend is reversed, however, for Ni which is 69% lower at the limed site (CON-07) than it is at the unlimed site (CON-08).

- Results of the two weaker extraction ($CaCl_2$ and the column leach) methods show the levels of Cu and Ni are much higher at the unlimed site, CON-08 ($CaCl_2$ Cu is 188% higher and Ni is 187% higher; column leach Cu is 112% higher and Ni is 183% higher) than at the limed site, CON-07.

These results indicate although the "total" levels of Cu and Ni at the limed site are higher, the "bioavailable" fraction as indicated by the $CaCl_2$ and column extractions, may in fact be much lower. This may be in part due to the large difference in pH and Ca between these two sites. Since both pH and Ca are well known modifiers of metal toxicity, metal bioavailability in the low pH soil at the unlimed (CON-08) would be expected to be much higher than in the limed soil (CON-07).

3.14.2.7 Summary of CON-07 to CON-08 Comparison

The plant community at CON-07 and CON-08, although in close proximity to each other, were in fact remarkably different. The limed site (CON-07) showed evidence of being a site in transition, while CON-08 was ranked as severely impacted. The past liming and re-greening activities have helped to establish a diverse plant community, with the introduction of essential minerals (Ca, Mg), providing a viable seed source, and increasing the soil pH thereby decreasing metal availability. Although CON-07 is not as productive as the established reference sites, the data collected from the four LOE indicate that it is on its way to re-establishing itself, as compared to CON-08, and that the re-greening activities employed within the Sudbury region are working.

On the other hand, without the addition of lime, seed source or strategic planting, CON-08 has retained its barren appearance and its status as a severely impacted site. Soil erosion, lack of organic matter and poor community structure all indicate that the site is still impacted. These results indicate that a variety of factors are contributing to the lack of recovery at CON-08 including: low soil fertility, low pH, lack of a growth medium and the increased bioavailability of metals in the soil.

3.14.3 Summary of the Role of pH in Objective #1

Although soil pH was not a COC in this study it was recognized that soil pH plays a significant role in affecting metal bioavailability and metal toxicity as well as direct soil toxicity. A considerable amount of effort was devoted to examining the role of soil pH and its interaction with metal toxicity in this study.

The studies conducted to examine these interactions were not intended to be exhaustive or definitive, but to provide valuable information. Some of the salient findings are:

- The pH in Sudbury soils is low enough (either naturally or with additional depositional effects) to inhibit the growth of some of the toxicity test plant species.
- The low pH of Sudbury soil totally inhibited earthworm reproduction.
- Raising soil pH to 5.2 improved measured toxicity endpoints (seedling emergence, biomass, root and shoot length and weight) of the two plant species tested in the majority of instances. The higher pH also resulted in the onset of earthworm reproduction in the site soil from many sites.
- Other soil variables (*e.g.*, fertility, organic content, soil development) play significant roles influencing the growth potential of the test site soils.

3.15 Bioavailability of Metals in the Sudbury Soils

As a side investigation to the Sudbury Soils Study a series of soil samples from the three transects were sent to an independent research laboratory for analysis of potentially plant available metal fractions.

Sub samples of the homogenized soil were given to Dr. William Hendershot in the Department of Natural Resource Science at McGill University, Quebec. Four extraction techniques were employed, where a detailed description of the rationale, procedures and methods involved is located in Appendix GD7-4. The four extraction procedures are presented in the order of decreasing strength (Table 3.54) and are described below.

The partial extraction methods here are different to those of the water leach approach previously discussed in this report (Section 3.3.4). The intent of applying four different extraction methods in the same laboratory was to compare the analytical results obtained from the extractions of differing strength. In addition, the results of the four analytical approaches were compared to the toxicity results, in order to attempt to determine the relationships between the additional extraction metal levels and the laboratory growth endpoints (Section 3.15.3).

3.15.1 Extraction Methods and Rationale

US EPA Method 3051: Nitric acid extraction

For general laboratory purposes the HNO_3 procedure provides a very good estimate of trace elements in contaminated soils. Although there are several alternate methods using HNO_3/HCl available, Alkema and Blum (2004) showed that EPA 3051 is the preferred method for the extraction of numerous elements for ICP-MS analysis. Nitric acid extractions were performed in two laboratories, Testmark (Garson, Ontario) as part of the Objective #1 soil LOE analyses, and McGill University, (Montreal, Quebec), under the supervision of Dr. William Hendershot, as part of an independent study. Extraction with nitric acid is often referred to as providing "total metal" levels. Only the "total" metal levels from the Hendershot lab are used for the following discussion.

0.05M NH_4-EDTA Method

Ethylenediaminetetraacetic acid (EDTA), a strong chelating agent can be used to remove trace elements from a wide range of surface adsorption/precipitation sites. Although this "fixed" metal would not be immediately available to plants or other soil organisms, studies show a good correlation between EDTA extractable metal and content in biological tissue (Ure 1996, De Gregori et al. 2004). The extraction with 0.05M EDTA was shown to be a good choice for estimating this "potentially available" fraction (Quevauviller 1998).

0.01M $CaCl_2$ Method

The use of neutral salt solutions such as $CaCl_2$, as extractants is promoted on the assumption that the photoavailable trace metals are mostly located on the soil mineral surfaces and therefore can be displaced by other cations. Unlike chelating extractants, such as EDTA, neutral salts remove the metal from the soil solid phase by saturating the soil with desorbing cations (McLaughlin et al., 2000). The $CaCl_2$ method is gaining support in Europe and North America as one of the best ways of evaluating bioavailability chemically (Houba et al. 1996, McBride et al. 2003, Bongers et al. 2004). The method has the advantage of being simple to use in the laboratory and the results are less variable between laboratories as compared to other extraction methods (Quevauviller 1998).

Table 3.54 Summary of the Bioavailability Analysis for Metals Conducted at McGill University

Category	Parameter	Units	Soil Sample Analyzed	Facility	Method	Location of Results
Metals	Total Metals (HNO_3)	mg/kg	Homogenized soil	McGill	Microwave digest by Method 3051	Appendix GD-7-4b
	EDTA Metals	mg/kg	Homogenized soil	McGill	Extraction with 0.05 M NH_4-EDTA	Appendix GD-7-4b
	$CaCl_2$-Metals	mg/kg	Homogenized soil	McGill	Extraction with 0.01 M $CaCl_2$ (adaptation of Quevauviller, 1998)	Appendix GD-7-4b
	Column-leach Metals	L/kg	Homogenized soil	McGill	Column leach with water and 80 µM $CaCl_2/CaSO_4$	Appendix GD-7-4b

Column Leach Method: 80µM $CaCl_2/CaSO_4$ and water solution

The column leaching technique was developed in the laboratory of Dr. William Hendershot and provides a very good simulation of the solubility of trace elements, pH and ionic strength of solutions collected in the field from forested soils in Ontario and Quebec, Canada (MacDonald *et al*., 2004a, b). This method consists of an initial washing of the soil with deionized water, followed by an equilibration with very dilute (80 µM) $CaCl_2$ and $CaSO_4$ solution to simulate the ionic strength observed in field soils. This method was chosen as it is the extraction procedure best suited to estimate metal mobility under field conditions (MacDonald *et al*., 2004b).

3.15.2 Results

Four different extraction methods (Appendix GD7-4a) were performed (McGill University in Montreal, Quebec), to better understand the relationship between the potentially bioaccessible metal fractions and the toxicity test endpoints (root/shoot length and weight). The results are provided in Appendix GD7-4b.

Figures 3-33 to 3-36 show the concentration of Ni and Cu for each of the four extraction techniques. The samples are grouped by transect and arranged in order of increasing distance from smelter.

Overall, the results show a positive relationship between extractant strength and the amount of metal in solution. The following discussion examines the results by extraction type for Ni and Cu across the three transects.

On average the EDTA extractions estimated about 34% of the total (HNO_3) Cu extracted concentrations and 16% of the total (HNO_3) Ni extractants. For the Copper Cliff transect the EDTA concentrations were between 27.98 mg/kg - 237.59 mg/kg for Cu and 2.47 mg/kg - 30.43 mg/kg for Ni. The Coniston concentrations were found to be lower and ranged from 12.18 mg/kg - 63.28 mg/kg EDTA Cu and 3.09 mg/kg - 35.96 mg/kg EDTA Ni. In comparison, the Falconbridge concentrations were more in line with those seen at Copper Cliff, and ranged between 23.82 mg/kg - 208.66 mg/kg for Cu and 9.51 mg/kg - 33.95 mg/kg for Ni. The reference sites ranged from 5.68 mg/kg - 17.8 mg/kg for Cu and 5.15 mg/kg - 7.07 mg/kg for Ni, which is well below the test sites.

The $CaCl_2$ extraction results were on average an order of magnitude lower than the EDTA results. Copper $CaCl_2$ concentrations were approximately 2% of the total (HNO_3) concentrations while Ni $CaCl_2$ concentrations tended to average just below 9% of the total.

The column leaching method was the weakest extraction technique and produced the lowest COC concentrations of the four methods. Overall this method extracted about 0.04 % of the total (HNO_3) Cu concentrations and 0.10% of the total Ni. The concentrations were on average two orders of magnitude below the $CaCl_2$ concentrations, and are in the range of parts per billion (ppb) as opposed to the other extractions that were in the parts per million (ppm) range.

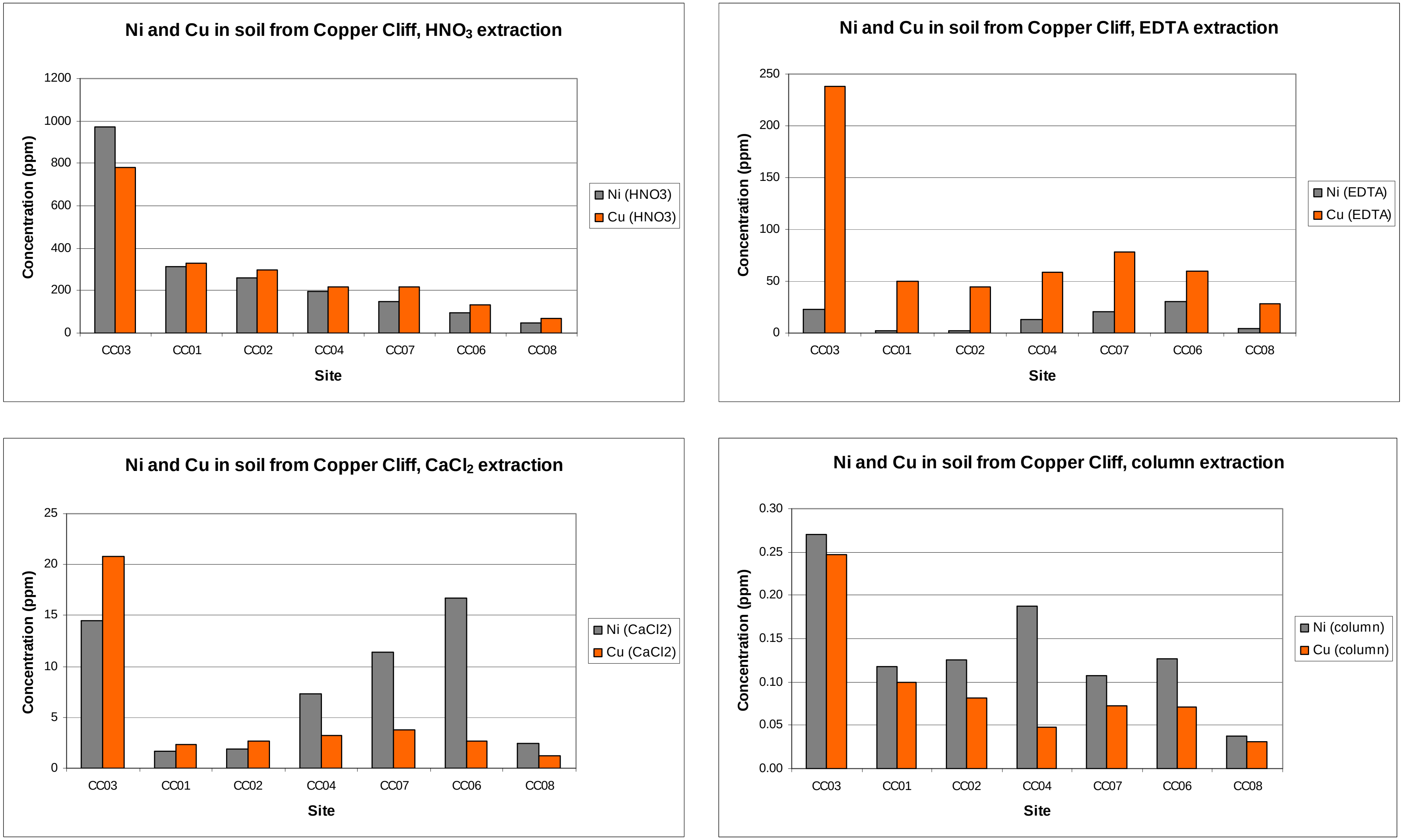
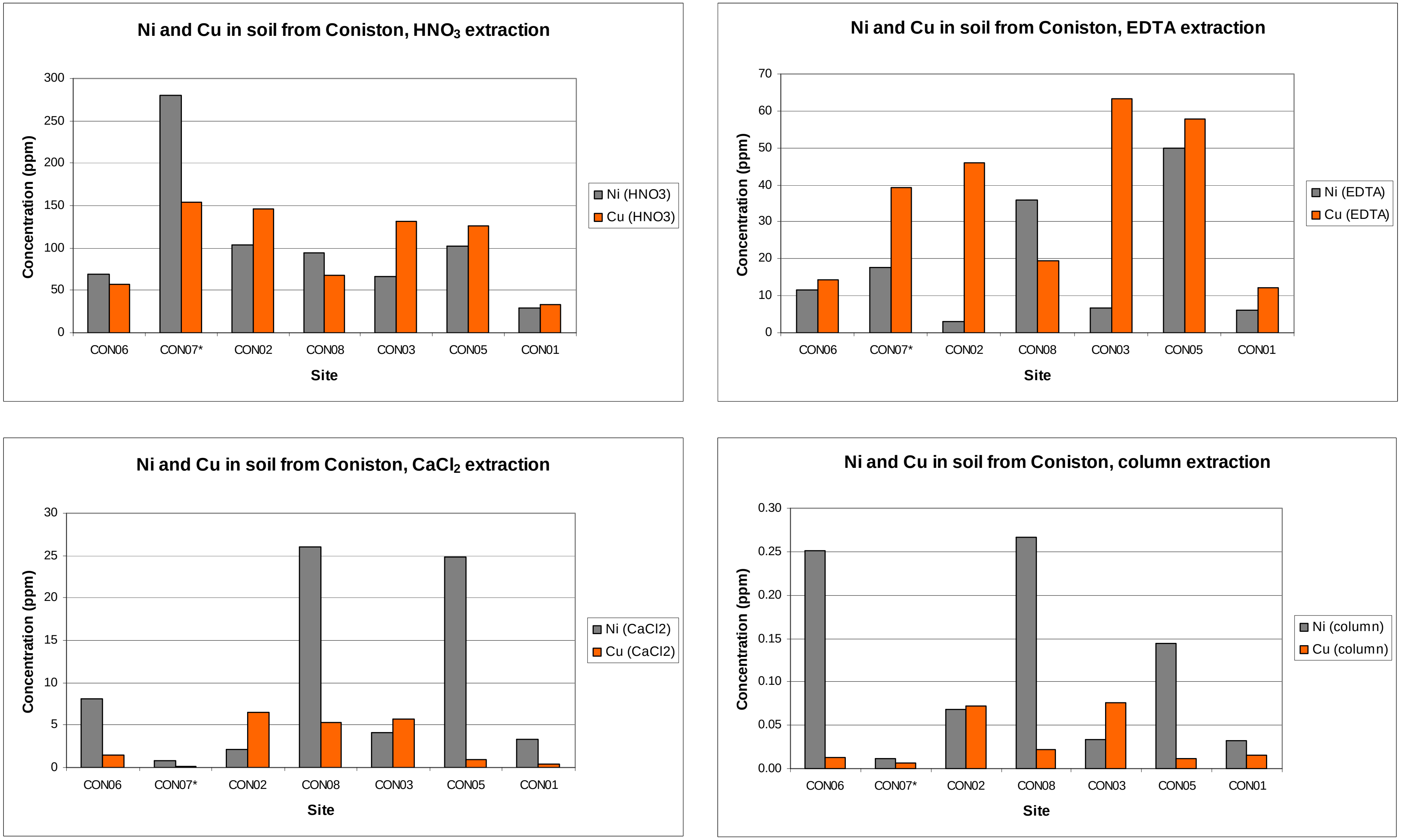


Figure 3-33 Nickel and copper concentrations measured in Copper Cliff soils using the four different extraction techniques.



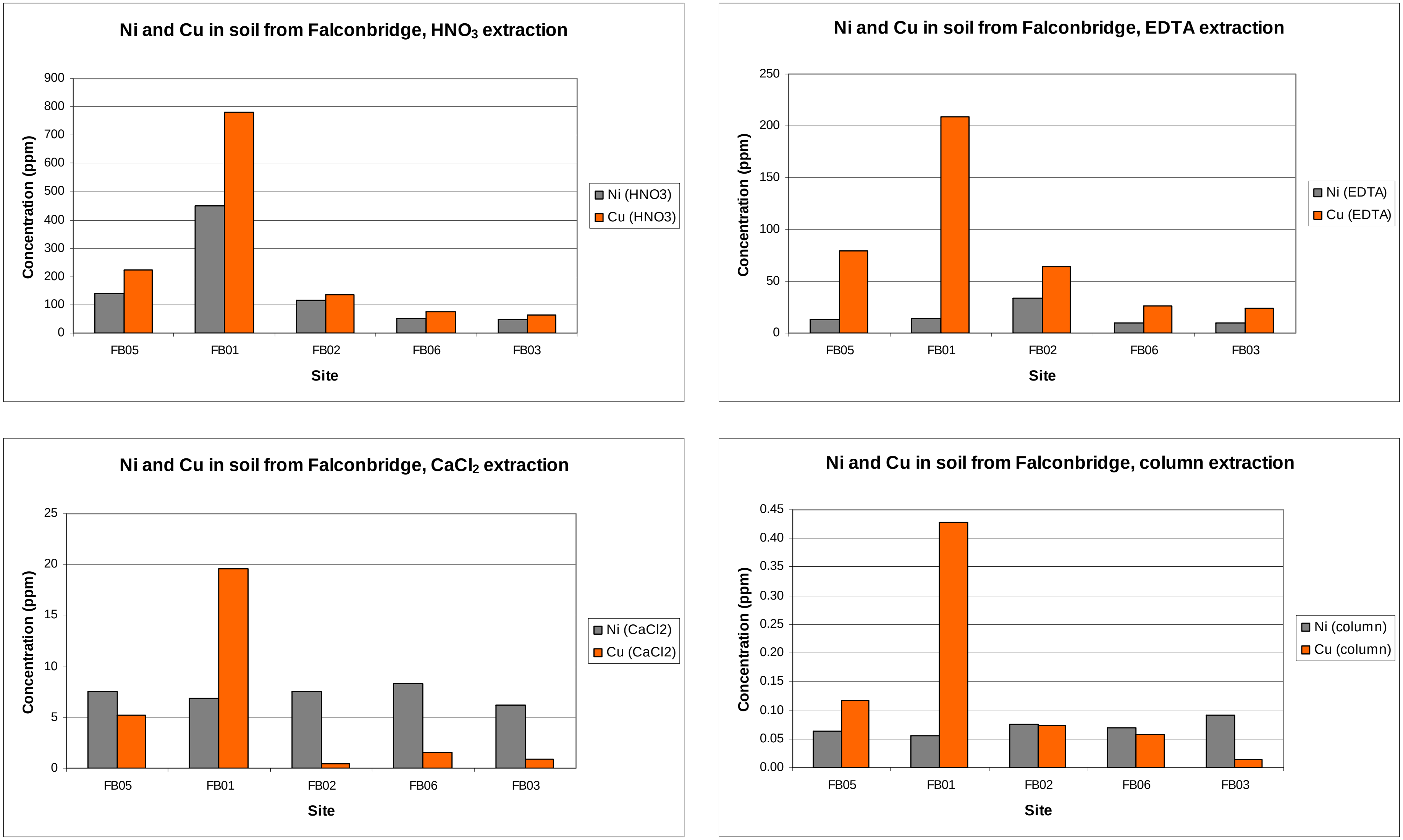
Ni and Cu in soil from Coniston, HNO_3 extraction

Ni and Cu in soil from Coniston, EDTA extraction

Ni and Cu in soil from Coniston, $CaCl_2$ extraction

Ni and Cu in soil from Coniston, column extraction

Figure 3-34 Nickel and copper concentrations measured in Coniston soils using the four different extraction techniques. (Note: CON-07 is the historically limed and re-greened site.)



Ni and Cu in soil from Falconbridge, HNO_3 extraction

Ni and Cu in soil from Falconbridge, EDTA extraction

Ni and Cu in soil from Falconbridge, $CaCl_2$ extraction

Ni and Cu in soil from Falconbridge, column extraction

Figure 3-35 Nickel and copper concentrations measured in Falconbridge soils using the four different extraction techniques.

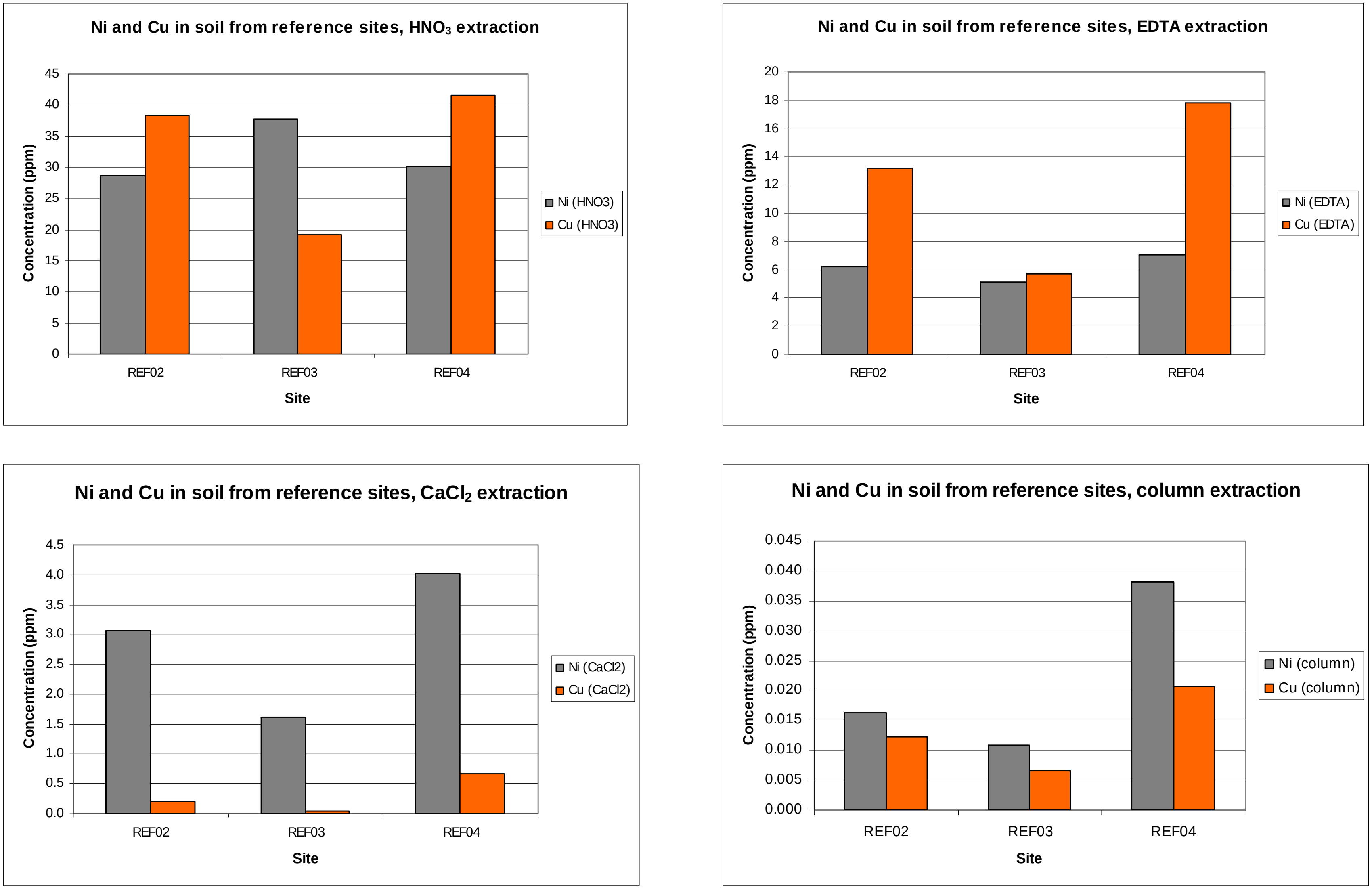


Figure 3-36 Nickel and copper concentrations measured in reference soils using the four different extraction techniques.

3.15.3 Statistical Comparison of Chemical Extractions with Toxicity Results

Statistical analyses were performed on the four extraction results and plant LOE toxicity test measurements (root/shoot length and weight). The following section outlines the types of analysis performed and the results. The purpose of the analysis was to determine if metal concentrations from any extraction method were better related to the toxicity endpoints when looking at the COC concentrations individually and then again as a unit (total COC).

3.15.3.1 Ni and Cu individually

Nickel and copper were the focus of the first statistical analysis, where the concentrations of the four extractions (HNO_3, EDTA, $CaCl_2$ and the column leach) were compared to the mean percent of the three reference soil toxicity plant tests (REF_{mean}) for each of the endpoint measurements (root/shoot length and weight) and each of the four species grown (goldenrod, red clover, northern wheatgrass and white spruce). Table 3.55 provides the data for the Copper Cliff transect.

Table 3.55 Copper Cliff Transect Plant Toxicity Data for Four Plant Species: Percent of Reference Site Conditions

Plant Species	Site	Root Weight (% of Ref_{mean})	Root Length (% of Ref_{mean})	Shoot Weight (% of Ref_{mean})	Shoot Length (% of Ref_{mean})
Goldenrod	CC-01	7.88	1.61	4.53	9.06
	CC-02	7.88	3.92	5.12	11.96
	CC-03	na	na	3.96	10.95
	CC-04	11.03	4.93	3.52	10.52
	CC-06	22.58	3.62	8.42	16.43
	CC-07	11.20	6.83	4.47	16.21
	CC-08	22.31	67.54	68.14	112.49
White Spruce	CC-01	27.94	15.63	41.59	83.37
	CC-02	52.98	50.91	70.92	95.22
	CC-03	17.74	7.04	33.27	63.38
	CC-04	121.43	46.72	124.61	100.43
	CC-06	22.35	17.84	45.64	84.83
	CC-07	150.55	67.80	154.45	96.53
	CC-08	178.95	121.26	117.88	103.11
Red Clover	CC-01	51.98	15.67	117.74	97.29
	CC-02	33.94	20.48	109.08	93.55
	CC-03	66.41	13.27	129.58	68.04
	CC-04	29.32	18.32	84.31	93.93

Table 3.55 Copper Cliff Transect Plant Toxicity Data for Four Plant Species: Percent of Reference Site Conditions

Plant Species	Site	Root Weight (% of Ref$_{mean}$)	Root Length (% of Ref$_{mean}$)	Shoot Weight (% of Ref$_{mean}$)	Shoot Length (% of Ref$_{mean}$)
	CC-06	74.99	31.43	121.65	113.12
	CC-07	48.16	29.42	104.61	107.14
	CC-08	107.15	68.59	110.22	99.15
Northern Wheatgrass	CC-01	26.61	19.36	56.00	80.92
	CC-02	28.62	20.31	66.57	82.50
	CC-03	5.55	6.55	56.49	65.51
	CC-04	29.38	19.93	55.81	75.70
	CC-06	68.11	64.39	87.67	97.09
	CC-07	41.16	46.38	79.96	92.63
	CC-08	58.21	69.44	86.00	87.93

Pearson's product moment correlation analysis was then performed on the Ni and Cu data and expressed as the percent of REF$_{mean}$ for each test site as compared to each soil metal extraction separately.

The sample size for each transect was between 5 and 7. Data variability and sample size have an effect on the statistical power of an analysis. The low sample sizes and high variability of the data can increase the chance of type I and type II errors, however, the data were analyzed by transect to facilitate comparison. The SigmaPlot/SigmaStat output tables and Figures from the regression analyses are located in Appendix GD7-4b.

Copper Cliff Transect

Tables 3.56 and 3.57 provide the correlation coefficients and p-values for the Pearson's product moment correlation analysis performed on the Copper Cliff nickel and copper data sets, respectively. This analysis shows that the HNO_3 and column leach extractions were very similar in their relationship to the toxicity endpoints. Strong relationships ($p\text{-values} < 0.05$) were determined for all endpoints of goldenrod and northern wheatgrass (root/shoot length and weight), root length of white spruce and red clover, and shoot length of white spruce. The EDTA and $CaCl_2$ extraction results showed no significant relationships for any of the toxicity endpoints.

The Pearson correlation analysis of the Copper Cliff copper data set (Table 3.57) indicated that strong relationships exist between all four of the extraction types with the goldenrod and northern wheatgrass toxicity data (all endpoints have significant relationships except EDTA with shoot weight). Overall it can be seen that the statistical relationships are similar between the four extractions and that the copper soil metal concentrations appear to be more correlated to the toxicity endpoints (% REF_{mean}) than the nickel extractions.

Table 3.56 Pearson's Product Moment Correlation for Nickel from the Hendershot extractions from the Copper Cliff Transect

Ni HNO_3 vs	SW Gold	SL Gold	RW Gold	RL Gold	SW WS	SL WS	RW WS	RL WS	SW RC	SL RC	RW RC	RL RC	SW NWG	SL NWG	RW NWG	RL NWG
Correlation Coefficient	**-0.800**	**-0.801**	**-0.768**	**-0.901**	-0.499	**-0.770**	-0.590	**-0.806**	0.421	-0.696	-0.643	**-0.870**	**-0.876**	**-0.853**	**-0.929**	**-0.938**
p-value	**0.017**	**0.017**	**0.044**	**0.006**	0.208	**0.026**	0.123	**0.016**	0.299	0.055	0.085	**0.005**	**0.004**	**0.007**	**0.001**	**0.001**
Ni EDTA vs	SW Gold	SL Gold	RW Gold	RL Gold	SW WS	SL WS	RW WS	RL WS	SW RC	SL RC	RW RC	RL RC	SW NWG	SL NWG	RW NWG	RL NWG
Correlation Coefficient	-0.266	-0.269	-0.016	-0.191	0.067	-0.353	-0.061	-0.305	0.144	0.009	0.010	-0.177	0.112	0.003	-0.015	0.029
p-value	0.525	0.519	0.973	0.682	0.875	0.391	0.886	0.463	0.733	0.983	0.981	0.676	0.792	0.994	0.973	0.946
Ni $CaCl_2$ vs	SW Gold	SL Gold	RW Gold	RL Gold	SW WS	SL WS	RW WS	RL WS	SW RC	SL RC	RW RC	RL RC	SW NWG	SL NWG	RW NWG	RL NWG
Correlation Coefficient	-0.386	-0.388	-0.125	-0.322	-0.001	-0.427	-0.146	-0.409	0.192	-0.050	-0.100	-0.302	0.002	-0.088	-0.132	-0.097
p-value	0.344	0.342	0.789	0.481	0.998	0.291	0.729	0.314	0.649	0.906	0.814	0.467	0.995	0.835	0.756	0.820
Ni Column vs	SW Gold	SL Gold	RW Gold	RL Gold	SW WS	SL WS	RW WS	RL WS	SW RC	SL RC	RW RC	RL RC	SW NWG	SL NWG	RW NWG	RL NWG
Correlation Coefficient	**-0.937**	**-0.907**	**-0.819**	**-0.973**	-0.370	-0.633	-0.511	**-0.845**	0.268	-0.438	**-0.743**	**-0.956**	**-0.818**	**-0.731**	**-0.858**	**-0.890**
p-value	**0.001**	**0.002**	**0.024**	**0.000**	0.368	0.092	0.195	**0.008**	0.521	0.278	**0.035**	**0.000**	**0.013**	**0.039**	**0.006**	**0.003**

*Text in **BOLD** indicates a statistically significant relationship
*SW= Shoot weight; SL= Shoot length; RW= Root weight, RL=Root length
*Gold= Goldenrod; WS= White Spruce; RC= Red Clover; NWG= Northern wheatgrass

Table 3.57 Pearson's Product Moment Correlation for Copper from the Hendershot extractions from the Copper Cliff Transect

Cu HNO_3 vs	SW Gold	SL Gold	RW Gold	RL Gold	SW WS	SL WS	RW WS	RL WS	SW RC	SL RC	RW RC	RL RC	SW NWG	SL NWG	RW NWG	RL NWG
Correlation Coefficient	**-0.869**	**-0.833**	**-0.862**	**-0.941**	-0.432	**-0.716**	-0.524	**-0.789**	0.415	-0.604	-0.681	**-0.925**	**-0.872**	**-0.821**	**-0.954**	**-0.952**
p-value	**0.005**	**0.010**	**0.013**	**0.002**	0.285	**0.046**	0.182	**0.020**	0.306	0.113	0.063	**0.001**	**0.005**	**0.013**	**0.000**	**0.000**
Cu EDTA vs	SW Gold	SL Gold	RW Gold	RL Gold	SW WS	SL WS	RW WS	RL WS	SW RC	SL RC	RW RC	RL RC	SW NWG	SL NWG	RW NWG	RL NWG
Correlation Coefficient	**-0.793**	**-0.725**	**-0.878**	**-0.936**	-0.337	**-0.771**	-0.412	**-0.730**	0.487	-0.547	-0.463	**-0.816**	-0.666	**-0.716**	**-0.823**	**-0.771**
p-value	**0.019**	**0.042**	**0.009**	**0.002**	0.415	**0.025**	0.311	**0.040**	0.221	0.161	0.248	**0.014**	0.071	**0.046**	**0.012**	**0.025**
Cu $CaCl_2$ vs	SW Gold	SL Gold	RW Gold	RL Gold	SW WS	SL WS	RW WS	RL WS	SW RC	SL RC	RW RC	RL RC	SW NWG	SL NWG	RW NWG	RL NWG
Correlation Coefficient	**-0.801**	**-0.716**	**-0.941**	**-0.943**	-0.343	**-0.741**	-0.399	-0.706	0.468	-0.594	-0.493	**-0.838**	**-0.715**	**-0.775**	**-0.872**	**-0.821**
p-value	**0.017**	**0.046**	**0.002**	**0.001**	0.406	**0.035**	0.328	0.051	0.243	0.120	0.214	**0.009**	**0.046**	**0.024**	**0.005**	**0.013**
Cu Column vs	SW Gold	SL Gold	RW Gold	RL Gold	SW WS	SL WS	RW WS	RL WS	SW RC	SL RC	RW RC	RL RC	SW NWG	SL NWG	RW NWG	RL NWG
Correlation Coefficient	**-0.838**	-0.780	**-0.881**	**-0.947**	-0.544	**-0.820**	-0.596	**-0.815**	0.631	-0.532	-0.509	**-0.879**	**-0.735**	**-0.715**	**-0.870**	**-0.845**
p-value	**0.009**	0.223	**0.009**	**0.001**	0.163	**0.013**	0.119	**0.014**	0.094	0.175	0.197	**0.004**	**0.038**	**0.046**	**0.005**	**0.008**

*Text in **BOLD** indicates a statistically significant relationship
*SW= Shoot weight; SL= Shoot length; RW= Root weight, RL=Root length
*Gold= Goldenrod; WS= White Spruce; RC= Red Clover; NWG= Northern wheatgrass

Falconbridge Transect

Comparisons of the nickel concentrations to the toxicity test endpoints for each of the four extraction types are shown in Appendix GD4-7b. Table 3.58 provides the correlation coefficients and p-values for the Pearson Correlation analyses for each extraction type for nickel along the Falconbridge transect. Overall there are very few statistically significant relationships ($p < 0.05$). Relationships were only found between the HNO_3 nickel concentration and root length and weight of northern wheatgrass, while the EDTA nickel concentration was found to only correlate to the shoot length of white spruce. Both the $CaCl_2$ and column leach extractions were significantly correlated to goldenrod shoot length, weight and root length.

Similar findings were found for copper concentrations (Table 3.59). A relationship was detected between the root length of northern wheatgrass and the HNO_3 copper concentration; root length and weight of northern wheatgrass and copper EDTA; shoot length of northern wheatgrass and $CaCl_2$ copper; and with root length of goldenrod and the copper column leach extractant.

Table 3.58 Pearson's Product Moment Correlation for Nickel from the Hendershot extractions from the Falconbridge Transect

Ni HNO_3 vs	SW Gold	SL Gold	RW Gold	RL Gold	SW WS	SL WS	RW WS	RL WS	SW RC	SL RC	RW RC	RL RC	SW NWG	SL NWG	RW NWG	RL NWG
Correlation Coefficient	-0.620	-0.569	-0.812	-0.749	-0.152	-0.142	-0.105	-0.122	0.964	0.643	0.325	0.00451	-0.754	-0.779	**-0.856**	**-0.873**
p-value	0.189	0.238	0.095	0.145	0.774	0.788	0.843	0.817	**0.008**	0.242	0.594	0.994	0.084	0.068	**0.030**	**0.023**
Ni EDTA vs	SW Gold	SL Gold	RW Gold	RL Gold	SW WS	SL WS	RW WS	RL WS	SW RC	SL RC	RW RC	RL RC	SW NWG	SL NWG	RW NWG	RL NWG
Correlation Coefficient	-0.623	-0.559	-0.748	-0.601	-0.764	**-0.851**	-0.649	-0.721	0.675	0.222	-0.263	-0.231	-0.021	-0.0522	-0.781	-0.459
p-value	0.186	0.249	0.146	0.284	0.077	**0.032**	0.163	0.106	0.212	0.720	0.669	0.709	0.969	0.922	0.067	0.360
Ni $CaCl_2$ vs	SW Gold	SL Gold	RW Gold	RL Gold	SW WS	SL WS	RW WS	RL WS	SW RC	SL RC	RW RC	RL RC	SW NWG	SL NWG	RW NWG	RL NWG
Correlation Coefficient	**-0.957**	**-0.914**	-0.756	**-0.937**	-0.0301	-0.249	0.155	-0.0751	0.622	0.182	0.0691	-0.331	-0.0328	-0.139	-0.395	-0.132
p-value	**0.003**	**0.011**	0.140	**0.019**	0.955	0.634	0.769	0.888	0.262	0.770	0.912	0.587	0.951	0.792	0.439	0.803
Ni Column vs	SW Gold	SL Gold	RW Gold	RL Gold	SW WS	SL WS	RW WS	RL WS	SW RC	SL RC	RW RC	RL RC	SW NWG	SL NWG	RW NWG	RL NWG
Correlation Coefficient	**-0.895**	**-0.924**	-0.761	**-0.901**	0.0102	-0.253	0.189	-0.0987	0.348	-0.217	-0.298	-0.718	0.105	-0.0828	-0.335	-0.0823
p-value	**0.016**	**0.008**	0.135	**0.037**	0.985	0.628	0.719	0.852	0.566	0.726	0.626	0.172	0.844	0.876	0.516	0.877

*Text in **BOLD** indicates a statistically significant relationship

*SW= Shoot weight; SL= Shoot length; RW= Root weight, RL=Root length

*Gold= Goldenrod; WS= White Spruce; RC= Red Clover; NWG= Northern wheatgrass

Table 3.59 Pearson's Product Moment Correlation for Copper from the Hendershot extractions from the Falconbridge Transect

Cu HNO$_3$ vs	SW Gold	SL Gold	RW Gold	RL Gold	SW WS	SL WS	RW WS	RL WS	SW RC	SL RC	RW RC	RL RC	SW NWG	SL NWG	RW NWG	RL NWG
Correlation Coefficient	-0.676	-0.631	-0.810	-0.796	-0.0477	-0.0598	0.00906	-0.0311	0.944	0.610	0.382	-0.0522	-0.753	-0.795	-0.808	**-0.833**
p-value	0.140	0.179	0.097	0.107	0.928	0.910	0.986	0.953	**0.016**	0.274	0.525	0.934	0.084	0.059	0.052	**0.040**
Cu EDTA vs	SW Gold	SL Gold	RW Gold	RL Gold	SW WS	SL WS	RW WS	RL WS	SW RC	SL RC	RW RC	RL RC	SW NWG	SL NWG	RW NWG	RL NWG
Correlation Coefficient	-0.708	-0.656	-0.844	-0.816	-0.167	-0.187	-0.104	-0.129	0.943	0.573	0.274	-0.0836	-0.670	-0.720	**-0.853**	**-0.829**
p-value	0.116	0.157	0.073	0.092	0.752	0.723	0.845	0.807	**0.016**	0.313	0.656	0.894	0.145	0.106	**0.031**	**0.041**
Cu CaCl$_2$ vs	SW Gold	SL Gold	RW Gold	RL Gold	SW WS	SL WS	RW WS	RL WS	SW RC	SL RC	RW RC	RL RC	SW NWG	SL NWG	RW NWG	RL NWG
Correlation Coefficient	-0.596	-0.574	-0.569	-0.711	0.402	0.384	0.438	0.400	0.595	0.506	0.690	0.0378	-0.753	**-0.816**	-0.470	-0.617
p-value	0.212	0.234	0.317	0.178	0.429	0.453	0.385	0.432	0.290	0.384	0.198	0.952	0.084	**0.048**	0.347	0.192
Cu Column vs	SW Gold	SL Gold	RW Gold	RL Gold	SW WS	SL WS	RW WS	RL WS	SW RC	SL RC	RW RC	RL RC	SW NWG	SL NWG	RW NWG	RL NWG
Correlation Coefficient	-0.648	-0.560	-0.863	**-0.889**	-0.111	-0.118	-0.0351	-0.0771	0.951	0.778	0.552	0.290	-0.663	-0.638	-0.709	-0.674
p-value	0.164	0.248	0.060	**0.044**	0.835	0.825	0.947	0.885	**0.013**	0.121	0.335	0.636	0.151	0.173	0.115	0.142

*Text in **BOLD** indicates a statistically significant relationship

*SW= Shoot weight; SL= Shoot length; RW= Root weight, RL=Root length

*Gold= Goldenrod; WS= White Spruce; RC= Red Clover; NWG= Northern wheatgrass

Coniston Transect

No significant statistical relationships were found for the nickel extractions from the Coniston soils, as shown in Table 3.60 (p-values were greater than 0.05). For the copper data (Table 3.61), only the $CaCl_2$ extraction showed relationships between the toxicity test endpoints. Significant correlation was found between $CaCl_2$ copper and the shoot length, weight and root length of goldenrod. All the growth parameters (root/shoot length and weight) for northern wheatgrass were significantly related to $CaCl_2$ copper, while only the root length of white spruce had a strong relationship.

Table 3.60 Pearson's Product Moment Correlation for Nickel from the Hendershot extractions from the Coniston Transect

Ni HNO_3 vs	SW Gold	SL Gold	RW Gold	RL Gold	SW WS	SL WS	RW WS	RL WS	SW RC	SL RC	RW RC	RL RC	SW NWG	SL NWG	RW NWG	RL NWG
Correlation Coefficient	-0.387	-0.301	-0.591	-0.198	0.131	0.530	0.213	0.0862	0.659	0.0552	0.618	-0.148	-0.0667	-0.166	-0.369	-0.195
p-value	0.344	0.469	0.162	0.671	0.758	0.177	0.612	0.839	0.075	0.897	0.102	0.726	0.875	0.694	0.368	0.643
Ni EDTA vs	SW Gold	SL Gold	RW Gold	RL Gold	SW WS	SL WS	RW WS	RL WS	SW RC	SL RC	RW RC	RL RC	SW NWG	SL NWG	RW NWG	RL NWG
Correlation Coefficient	0.189	0.223	0.718	0.221	-0.465	0.0979	-0.494	-0.124	0.332	-0.0881	0.497	0.115	-0.0353	0.0220	-0.0916	-0.0624
p-value	0.654	0.595	0.069	0.635	0.246	0.818	0.213	0.769	0.421	0.836	0.210	0.786	0.934	0.959	0.829	0.883
Ni $CaCl_2$ vs	SW Gold	SL Gold	RW Gold	RL Gold	SW WS	SL WS	RW WS	RL WS	SW RC	SL RC	RW RC	RL RC	SW NWG	SL NWG	RW NWG	RL NWG
Correlation Coefficient	0.119	0.164	0.640	0.169	-0.463	0.162	-0.484	-0.150	0.376	-0.104	0.533	0.0601	-0.0762	-0.0313	-0.172	-0.119
p-value	0.779	0.698	0.122	0.717	0.248	0.702	0.224	0.723	0.359	0.806	0.174	0.888	0.858	0.941	0.684	0.779
Ni Column vs	SW Gold	SL Gold	RW Gold	RL Gold	SW WS	SL WS	RW WS	RL WS	SW RC	SL RC	RW RC	RL RC	SW NWG	SL NWG	RW NWG	RL NWG
Correlation Coefficient	-0.443	-0.356	-0.254	-0.326	-0.0633	0.479	-0.0414	-0.154	0.408	-0.146	0.438	-0.367	-0.166	-0.230	-0.486	-0.270
p-value	0.272	0.387	0.583	0.475	0.882	0.230	0.922	0.715	0.315	0.729	0.278	0.371	0.695	0.583	0.222	0.518

*Text in **BOLD** indicates a statistically significant relationship

*SW= Shoot weight; SL= Shoot length; RW= Root weight, RL=Root length

*Gold= Goldenrod; WS= White Spruce; RC= Red Clover; NWG= Northern wheatgrass

Table 3.61 Pearson's Product Moment Correlation for Copper and the Hendershot extractions from the Coniston Transect

Cu HNO_3 vs	SW Gold	SL Gold	RW Gold	RL Gold	SW WS	SL WS	RW WS	RL WS	SW RC	SL RC	RW RC	RL RC	SW NWG	SL NWG	RW NWG	RL NWG
Correlation Coefficient	-0.0157	-0.0473	-0.416	-0.0874	-0.641	0.354	-0.606	-0.349	0.237	-0.0268	0.376	-0.202	-0.589	-0.600	-0.564	-0.443
p-value	0.971	0.911	0.353	0.852	0.087	0.390	0.111	0.396	0.572	0.950	0.358	0.631	0.124	0.116	0.145	0.272
Cu EDTA vs	SW Gold	SL Gold	RW Gold	RL Gold	SW WS	SL WS	RW WS	RL WS	SW RC	SL RC	RW RC	RL RC	SW NWG	SL NWG	RW NWG	RL NWG
Correlation Coefficient	-0.143	-0.144	-0.443	-0.125	-0.460	0.473	-0.431	-0.194	0.347	-0.0885	0.503	-0.163	-0.521	-0.513	-0.469	-0.335
p-value	0.735	0.734	0.320	0.790	0.251	0.237	0.287	0.646	0.399	0.835	0.204	0.700	0.186	0.193	0.242	0.418
Cu $CaCl_2$ vs	SW Gold	SL Gold	RW Gold	RL Gold	SW WS	SL WS	RW WS	RL WS	SW RC	SL RC	RW RC	RL RC	SW NWG	SL NWG	RW NWG	RL NWG
Correlation Coefficient	**-0.732**	**-0.808**	-0.344	**-0.864**	-0.543	-0.458	-0.480	**-0.756**	-0.0308	-0.669	0.209	-0.669	**-0.877**	**-0.909**	**-0.875**	**-0.920**
p-value	**0.039**	**0.015**	0.450	**0.012**	0.164	0.253	0.228	**0.030**	0.942	0.070	0.620	0.070	**0.004**	**0.002**	**0.004**	**0.001**
Cu Column vs	SW Gold	SL Gold	RW Gold	RL Gold	SW WS	SL WS	RW WS	RL WS	SW RC	SL RC	RW RC	RL RC	SW NWG	SL NWG	RW NWG	RL NWG
Correlation Coefficient		-0.614	-0.625	-0.628	-0.198	-0.0934	-0.0945	-0.326	0.324	-0.384	0.429	-0.310	-0.617	-0.659	-0.622	-0.672
p-value		0.106	0.133	0.131	0.638	0.826	0.824	0.431	0.434	0.347	0.289	0.455	0.103	0.075	0.099	0.068

*Text in **BOLD** indicates a statistically significant relationship

*SW= Shoot weight; SL= Shoot length; RW= Root weight, RL=Root length

*Gold= Goldenrod; WS= White Spruce; RC= Red Clover; NWG= Northern wheatgrass

3.15.3.2 COC in Conjunction

The result of no one extraction technique for Ni and Cu were consistently correlated to the plant toxicity data. The next step was to combine the COC for each of the extraction techniques relative to the plant toxicity results. The seven COC concentrations (As, Cd, Co, Cu, Ni, Pb, Se) were summed for each of the four soil extraction techniques and compared to the converted (% of REF_{mean}) toxicity test endpoints. Again the data are described by transect to facilitate comparisons.

Copper Cliff Transect

The nitric acid and column leach data were highly correlated to each other. Of the 16 potential relationships, eleven were developed with the nitric acid *all* COC analysis (Table 3.62), while the column leach concentrations were found to correlate with ten of those eleven. The EDTA extraction had fewer relationships when looking at the metals in conjunction, where as the $CaCl_2$ extractions had no statistically significant relationships with the toxicity test endpoints when looking at the seven COC in conjunction.

Table 3.62 Pearson's Product Moment Correlation for the COC from the Hendershot extractions from the Copper Cliff Transect

HNO_3 vs	SW Gold	SL Gold	RW Gold	RL Gold	SW WS	SL WS	RW WS	RL WS	SW RC	SL RC	RW RC	RL RC	SW NWG	SL NWG	RW NWG	RL NWG
Correlation Coefficient	**-0.819**	**-0.805**	**-0.810**	**-0.916**	-0.476	**-0.756**	-0.563	**-0.795**	0.429	-0.674	-0.648	**-0.886**	**-0.873**	**-0.847**	**-0.942**	**-0.943**
P Value	**0.013**	**0.016**	**0.027**	**0.004**	0.234	**0.030**	0.146	**0.019**	0.289	0.067	0.082	**0.003**	**0.005**	**0.008**	**0.000**	**0.000**
EDTA vs	SW Gold	SL Gold	RW Gold	RL Gold	SW WS	SL WS	RW WS	RL WS	SW RC	SL RC	RW RC	RL RC	SW NWG	SL NWG	RW NWG	RL NWG
Correlation Coefficient	**-0.727**	-0.688	-0.703	**-0.848**	-0.314	**-0.776**	-0.415	**-0.720**	0.479	-0.477	-0.381	**-0.726**	-0.530	-0.600	-0.690	-0.641
P Value	**0.041**	0.059	0.078	**0.016**	0.449	**0.024**	0.307	**0.044**	0.229	0.232	0.351	**0.041**	0.176	0.116	0.058	0.087
$CaCl_2$ vs	SW Gold	SL Gold	RW Gold	RL Gold	SW WS	SL WS	RW WS	RL WS	SW RC	SL RC	RW RC	RL RC	SW NWG	SL NWG	RW NWG	RL NWG
Correlation Coefficient	-0.572	-0.563	-0.357	-0.566	-0.189	-0.639	-0.325	-0.596	0.360	-0.286	-0.248	-0.525	-0.251	-0.349	-0.409	-0.371
P Value	0.138	0.146	0.432	0.185	0.654	0.088	0.433	0.119	0.381	0.492	0.554	0.182	0.549	0.397	0.314	0.365
Column vs	SW Gold	SL Gold	RW Gold	RL Gold	SW WS	SL WS	RW WS	RL WS	SW RC	SL RC	RW RC	RL RC	SW NWG	SL NWG	RW NWG	RL NWG
Correlation Coefficient	**-0.924**	**-0.889**	**-0.858**	**-0.992**	-0.442	-0.705	-0.560	**-0.851**	0.385	-0.502	-0.700	**-0.954**	**-0.821**	**-0.758**	**-0.893**	**-0.910**
P Value	**0.000**	**0.003**	**0.014**	**0.000**	0.273	0.051	0.149	**0.007**	0.346	0.205	0.053	**0.000**	**0.012**	**0.029**	**0.003**	**0.002**

*Text in **BOLD** indicates a statistically significant relationship

*SW= Shoot weight; SL= Shoot length; RW= Root weight, RL=Root length

*Gold= Goldenrod; WS= White Spruce; RC= Red Clover; NWG= Northern wheatgrass

Falconbridge Transect

Overall, very few statistically significant correlations were found between the extractable metals from the Falconbridge soils (when looking at the COC in conjunction) and the plant species endpoints (Table 3.63). Only two statistical relationships (root length and weight of northern wheatgrass) were seen with the nitric acid and EDTA extractions. The column leach and $CaCl_2$ extractions were only correlated to the endpoints of goldenrod.

Table 3.63 Pearson's Product Moment Correlation for the COC from the Hendershot extractions from the Falconbridge Transect

HNO_3 vs	SW Gold	SL Gold	RW Gold	RL Gold	SW WS	SL WS	RW WS	RL WS	SW RC	SL RC	RW RC	RL RC	SW NWG	SL NWG	RW NWG	RL NWG
Correlation Coefficient	-0.639	-0.588	-0.818	-0.769	-0.123	-0.121	-0.071	-0.100	0.966	0.642	0.347	-0.001	-0.756	-0.783	**-0.842**	**-0.858**
P Value	0.172	0.220	0.090	0.128	0.816	0.820	0.893	0.850	**0.007**	0.243	0.567	0.988	0.082	0.066	**0.035**	**0.029**
EDTA vs	SW Gold	SL Gold	RW Gold	RL Gold	SW WS	SL WS	RW WS	RL WS	SW RC	SL RC	RW RC	RL RC	SW NWG	SL NWG	RW NWG	RL NWG
Correlation Coefficient	-0.688	-0.633	-0.875	-0.792	-0.295	-0.313	-0.226	-0.263	0.915	0.521	0.139	-0.098	-0.644	-0.678	**-0.910**	**-0.847**
P Value	0.130	0.178	0.052	0.110	0.570	0.546	0.666	0.615	**0.029**	0.368	0.824	0.875	0.168	0.139	**0.012**	**0.033**
$CaCl_2$ vs	SW Gold	SL Gold	RW Gold	RL Gold	SW WS	SL WS	RW WS	RL WS	SW RC	SL RC	RW RC	RL RC	SW NWG	SL NWG	RW NWG	RL NWG
Correlation Coefficient	**-0.849**	-0.794	**-0.910**	**-0.951**	-0.047	-0.139	0.078	-0.083	0.823	0.430	0.244	-0.153	-0.618	-0.659	-0.747	-0.660
P Value	**0.032**	0.059	**0.032**	**0.013**	0.930	0.793	0.884	0.876	0.087	0.470	0.692	0.806	0.191	0.155	0.088	0.154
Column vs	SW Gold	SL Gold	RW Gold	RL Gold	SW WS	SL WS	RW WS	RL WS	SW RC	SL RC	RW RC	RL RC	SW NWG	SL NWG	RW NWG	RL NWG
Correlation Coefficient	**-0.852**	**-0.814**	**-0.919**	**-0.926**	-0.035	-0.134	0.088	-0.098	0.769	0.307	0.116	-0.305	-0.667	-0.722	-0.792	-0.721
P Value	**0.031**	**0.048**	**0.028**	**0.024**	0.947	0.801	0.869	0.853	0.129	0.615	0.853	0.617	0.148	0.105	0.060	0.106

*Text in **BOLD** indicates a statistically significant relationship
*SW= Shoot weight; SL= Shoot length; RW= Root weight, RL=Root length
*Gold= Goldenrod; WS= White Spruce; RC= Red Clover; NWG= Northern wheatgrass

Coniston Transect

When looking at all the COC in conjunction, there were no statistical relationships between the nitric acid and EDTA extractable metals with the toxicity test endpoints (Table 3.64). Relationships were seen with the $CaCl_2$ and column leach extractions, where the shoot weight/length and root length of goldenrod was inversely correlated to the metal concentrations from both extractions, along with the shoot and root length of red clover. The $CaCl_2$ extractable metals were also correlated to the shoot length of northern wheatgrass. Relationships were seen with the column leach extractions and the root length of white spruce as well as the root length and weight of northern wheatgrass.

Table 3.64 Pearson's Product Moment Correlation for the COC from the Hendershot extractions from the Coniston Transect

HNO_3 vs	SW Gold	SL Gold	RW Gold	RL Gold	SW WS	SL WS	RW WS	RL WS	SW RC	SL RC	RW RC	RL RC	SW NWG	SL NWG	RW NWG	RL NWG
Correlation Coefficient	0.205	0.148	-0.315	0.067	-0.699	0.275	-0.669	-0.332	0.158	0.118	0.274	-0.107	-0.501	-0.515	-0.460	-0.355
P Value	0.627	0.727	0.492	0.887	0.0539	0.509	0.0694	0.422	0.709	0.782	0.512	0.801	0.206	0.191	0.251	0.388
EDTA vs	SW Gold	SL Gold	RW Gold	RL Gold	SW WS	SL WS	RW WS	RL WS	SW RC	SL RC	RW RC	RL RC	SW NWG	SL NWG	RW NWG	RL NWG
Correlation Coefficient	-0.153	-0.208	-0.236	-0.228	-0.574	0.181	-0.576	-0.346	0.087	-0.193	0.322	-0.308	-0.563	-0.546	-0.462	-0.338
P Value	0.718	0.620	0.610	0.623	0.137	0.668	0.135	0.401	0.838	0.648	0.437	0.458	0.146	0.161	0.249	0.414
$CaCl_2$ vs	SW Gold	SL Gold	RW Gold	RL Gold	SW WS	SL WS	RW WS	RL WS	SW RC	SL RC	RW RC	RL RC	SW NWG	SL NWG	RW NWG	RL NWG
Correlation Coefficient	**-0.809**	**-0.871**	0.034	**-0.879**	-0.301	-0.528	-0.345	-0.674	-0.434	**-0.837**	-0.153	**-0.796**	-0.625	**-0.597**	-0.574	-0.571
P Value	**0.015**	**0.005**	0.943	**0.009**	0.469	0.179	0.403	0.067	0.283	**0.010**	0.718	**0.018**	0.097	**0.012**	0.136	0.139
Column vs	SW Gold	SL Gold	RW Gold	RL Gold	SW WS	SL WS	RW WS	RL WS	SW RC	SL RC	RW RC	RL RC	SW NWG	SL NWG	RW NWG	RL NWG
Correlation Coefficient	**-0.846**	**-0.902**	0.090	**-0.950**	-0.422	-0.642	-0.456	**-0.861**	-0.459	**-0.905**	-0.198	**-0.887**	-0.701	-0.691	**-0.746**	**-0.766**
P Value	**0.008**	**0.002**	0.848	**0.001**	0.297	0.086	0.257	**0.006**	0.253	**0.002**	0.638	**0.003**	0.053	0.058	**0.034**	**0.027**

*Text in **BOLD** indicates a statistically significant relationship
*SW= Shoot weight; SL= Shoot length; RW= Root weight, RL=Root length
*Gold= Goldenrod; WS= White Spruce; RC= Red Clover; NWG= Northern wheatgrass

3.15.4 Summary

The extraction analyses performed by Dr. William Hendershot at McGill University were statistically compared to the toxicity test endpoints (root and shoot length/weight) for each of the test species. The following observations were made:

- No one extraction best described the relationships between the soil metal concentration and the toxicity endpoints.
- The nitric acid and column leach extractions correlated with the most toxicity endpoints from the four test species.
- Stronger relationships were seen between the different copper and nickel concentrations with the goldenrod and northern wheatgrass endpoint compared to red clover and white spruce tests.
- When looking at metals in combination (all COC), the nitric acid and column leach results were most similar to the individual nickel and copper analyses.

In conclusion, no one extraction best described the toxicity test results when looking at both nickel and copper separately and the seven COC in conjunction. As this was the case, and based on this analysis, no observations on the effective way to measure soil metal bioavailability can be made. The statistical power of this analysis was low due to the natural variability in the data and the sample size. The lack of power in this analysis means that relationships may be present in the natural environment that could not be detected using the data analyzed.

It is suggested that further analysis of this data set, along with the data from the Soil LOE and the Plant Community LOE be compared to better understand the interactions between the soil metal concentrations and the potential availability and resultant toxicity that is seen at each of the sites. The results of this analysis, in combination with the total metals data, indicate that perhaps the soil metal concentrations are not the sole driving factors of toxicity, and that other factors are contributing to the lack of recovery at some of the test sites. Further analyses, which are outside the scope of this study are required to quantify this effect.

3.16 Overall Uncertainties Related to Objective #1

An important consideration of any risk assessment is to identify uncertainties associated with either the methodology, available information or results. These areas of uncertainty are subjectively evaluated and discussed with the purpose of providing confidence in the final results and conclusion.

A detailed discussion of uncertainty related to numerical measurements, data quality and parameter input is important for quantitative risk assessments relying on model outputs and model predictions. These types of uncertainties are discussed in Chapter 4 but are less applicable to the approach taken to evaluate Objective #1.

Risk managers need to be aware of the uncertainty surrounding the study conclusions so they can make recommendations and decisions accordingly.

Each LOE from the Objective #1 study has associated uncertainties that are discussed in detail in the individual ranking reports. Risk managers have to be aware of these uncertainties when making decisions with respect to the risk associated with the terrestrial plant community. Having said this, the SARA Group is confident with the approach taken for the Objective #1 study, and in the overall final ranking for each site. With respect to the amount of information collected and the present availability of supporting documentation, the SARA Group feels that there are no other tests and no other information that could be collected at this time that would change the final site ranking designations.

The overall uncertainties associated with the Objective #1 study are discussed below.

3.16.1 Reference Sites

The Sudbury region is in a transitional zone between the Great Lakes-Saint Lawrence Forest and the Boreal Forest Regions. It is also the location where four climatic zones intersect. For these reasons isolating reference sites that are applicable to all of the test sites was a challenge. This situation was further confounded by having only three reference sites to compare to the 18 test sites and one historically limed and re-greened site. The intent of the initial study design was to have three transects with similar soil properties, established along a metal gradient, with each transect having a corresponding representative reference or unimpacted site. However, due to the heterogeneity associated with the terrestrial community coupled with the interaction of four climatic zones and two forest zones, this could not be completely achieved. The individual reference sites did not completely represent all of the test sites in the corresponding transect, nor were all of the climatic zones entirely represented. Utilizing a greater number of reference sites would reduce uncertainty, however, we do not feel it would change the results or conclusions.

3.16.2 Sulphur Dioxide

Sulphur and sulphur dioxide, like pH, were not considered COC in this study but are known to have a significant effect on the landscape. In addition to the thousands of tonnes of metal particulates emitted over more than a century of smelting in the Sudbury area, more than 100 million tones of sulphur dioxide (SO_2) have also been released into the atmosphere (Lautenbach, 1985). In addition to the direct toxic effects of historic SO_2 fumigations on vegetation in the Sudbury region, wet deposition of SO_2 as sulfuric acid (i.e., acid rain) has increased the acidity of the already low soil pH in some areas. Deposition of acid rain has effectively leached nutrients from the organic-poor Sudbury soils and increased the soil mobility of metals deposited from smelter emissions. It was the combination of acidic soils and metal absorption that led to the mortality of virtually all but the metal-tolerant vegetation species and strains in some areas (Volume I, Chapter 4). The poor air and soil quality resulting from historic SO_2 emissions has most certainly affected the region's forests. Damage to poplar, white birch and cultivated plants due to SO_2 emissions has been repeatedly documented. Damage to trembling aspen has been observed as far as 100 km east and 77 km southwest of the City of Sudbury (Volume I, Chapter 4). The possible direct and indirect effects of SO_2 fumigation are conceptually shown Figure 3-37.

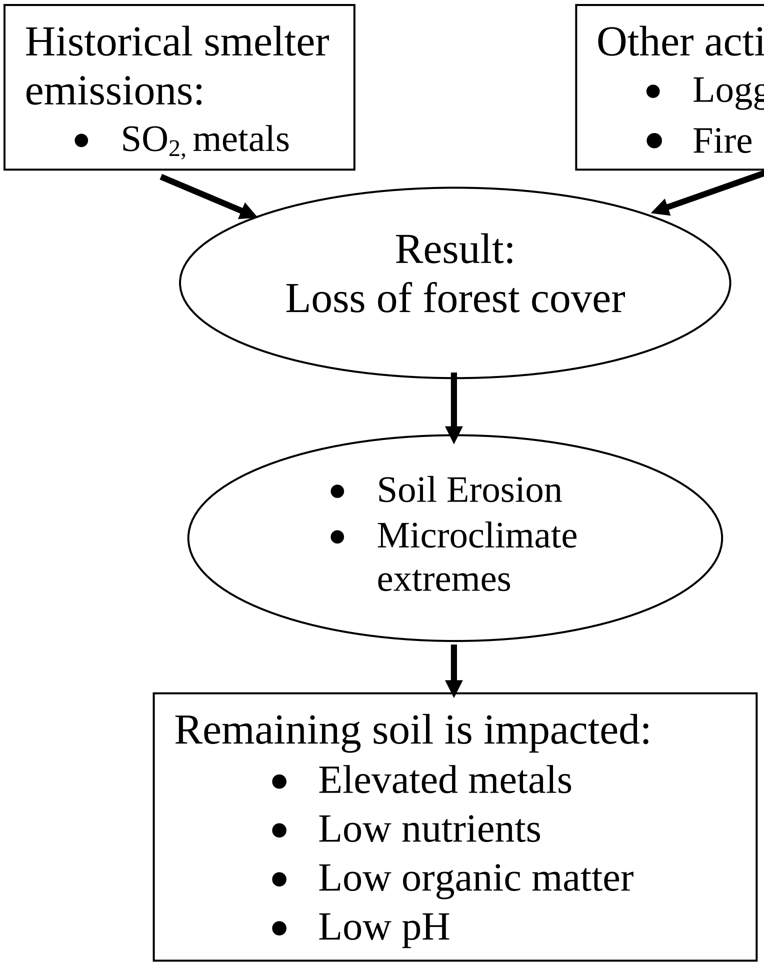


Figure 3-37 Conceptual linkages of historical smelter emissions and other activities leading to current soil conditions

Due to technological advances in processing sulphur ores (Volume I, Chapter 3), current SO_2 emissions are less than 10% of those 30 years ago and are not considered to be directly affecting area vegetation. However, the current plant community is affected by historical SO_2 emissions which caused vegetation kills in the past and contributed to a sequence of events that are currently impacting the community. Historic SO_2 emissions are, therefore, a potential confounding factor for the purposes of the current objective of evaluating the impact of COC in preventing the recovery of regionally representative selfsustaining terrestrial plant communities.

3.16.3 Bioavailability/Bioaccessibility

At present there is no standardized method of determining metal bioavailability that is widely accepted by the scientific community. The SARA Group's approach was to use a variety of methods to assess which one most accurately represented the bioavailable soil fraction that correlated with the toxicity testing endpoints (root/shoot length and weight).

Through this exercise, it was found that none of the partial extraction procedures were consistently better correlated with plant toxicity than the total metal results from the nitric acid extraction. Correlation of extraction results with plant toxicity ultimately depends on soil type, plant type, and metal or metals involved. Furthermore, the complex metal mixtures that are typically found in soils from the Sudbury region greatly confound attempts to determine toxicity based on a single variable (*i.e.*, concentration of a single metal). In addition, the heterogeneity of the site soils within and between transects, along with the large variety of soil physical and chemical characteristics all have to be taken into consideration when dealing with overall toxicity and bioavailability.

There was no clear analytical procedure that best fit all the data. Taking into consideration plant species and soil type, certain extraction methods fit the toxicity data better than others. A recommendation from this study is to further investigate the issue of bioavailability with respect to the Sudbury soils and the data generated from the Objective #1 studies.

3.16.4 Core versus Homogenized Bulk Soil Samples

Metals- Core Samples versus Homogenized Soil Samples

Total metal levels in the core and bulk samples are compared in Table 3.65. The difference in the results can be attributed to the fact that soil is not homogeneous and levels of metals will vary by sample based on a number of factors. Although precautions were undertaken to collect a large number of randomized soil core samples, there was still the potential to collect from a metal "hot spot" or conversely, from a location with lower-than-average metal concentrations. Repeated sampling of at least 50 sample cores at each site decreased the amount of possible variance found amongst the collected soil, but it is important to note that the quantity of soil collected to form the homogenized bulk soil sample was much larger than the amount of soil collected from the soil cores which may have resulted in some dilution and lower metal levels in the bulk samples.

Table 3.65 Summary of Total COC Concentrations in Soil Cores (0-5 cm) and Homogenized Soil from Test and Reference Sites

COC	**Range by Transect (µg/L)**						**Reference Sites**	
	Copper Cliff		**Falconbridge**		**Coniston**			
	Soil Core	Homogenized Soil	Soil Core	Homogenized Soil	Soil Core	Homogenized Soil	Soil Core	Homogenized Soil
Arsenic	9.6 – 72	3.6 – 79	10.9 – 117	9.5 – 183	2.1 – 28	2.5 – 13	2.66 – 5.85	2.7 – 6.3
Cadmium	0.27 – 1.26	<DL – 0.57	0.26 – 1.17	<DL – 1.1	0.12 – 0.44	0.1 – 0.46	0.17 – 0.28	<DL – 0.22
Cobalt	7.81 – 41.5	4.14 – 39.2	4.84 – 48.4	3.82 – 39.1	5.51 – 11.5	5.5 – 18	4.87 – 11.5	3.95 – 12
Copper	97 – 1000	41.2 – 948	87 – 655	67.5 – 909	48.7 – 240	32.1 – 170	18.7 – 42	18.7 – 40.7
Lead	17.2 – 99.5	9.3 – 106	28 – 162	16 – 226	4.6 – 35	4.5 – 17	14 – 33	15 – 26
Nickel	77.5 – 1100	27.2 – 1100	78 – 422	49.4 – 535	70.2 – 255	33.9 – 313	38.9 – 46	27.6 – 38.3
Selenium	1.4 – 10.5	0.51 – 9.6	1.1 – 5.6	0.64 – 8.2	0.3 – 1.1	0.44 – 1.1	0.48 – 1	0.5 – 0.92

Bulk soil was collected at each site for analytical determination and for use in the toxicity testing, while soil cores were collected for the majority of the physical and chemical characterization. It is to be expected that some differences exist between the total metal concentrations in the core and homogenized bulk soil samples. These differences are a source of uncertainty in the assessment; therefore, a comparison between total metal concentrations in core and homogenized bulk soil samples was made using regression analysis. The results of the analysis show that, in most cases, there was a good correlation between the levels of COC detected in the soil cores versus the levels detected in the homogenized soil (Table 3.66). This suggests that the distribution of metals across each site was relatively even and the soils collected for the study were representative of site conditions.

However, Cd is one exception. This may be attributed to the fact that levels of cadmium measured at the test sites are at least 10-fold lower than levels of the other metals, meaning that any differences in concentrations would result in larger differences in the R^2 values. The other exception is the Coniston transect. The lower correlation between total metal concentrations in the soil cores and bulk samples on the Coniston transect suggests that the distribution of metals in this area is quite distinct and patchy. As the soils along the Coniston transect were indicative of the greatest amount of soil/surface soil erosion, this patchy representation of metal concentration concurs with the overall assessment of these soils.

Table 3.66 Paired Sample Correlations for Total Metal Concentrations in Core and Homogenized Soil Samples

COC	All Test Sites (n=19)		Copper Cliff (n=7)		Coniston (n=7)		Falconbridge (n=5)	
	R	R^2	R	R^2	R	R^2	R	R^2
As	0.93	0.865	0.922	0.85	0.507	0.257	0.969	0.939
Cd	0.276	0.076	-0.0358	0.128	0.846	0.716	0.283	0.080
Co	0.919	0.845	0.0939	0.882	0.282	0.080	0.954	0.910
Cu	0.830	0.689	0.816	0.666	0.612	0.375	0.955	0.912
Ni	0.901	0.812	0.915	0.837	0.872	0.760	0.845	0.714
Pb	0.896	0.803	0.866	0.750	0.328	0.108	0.936	0.876
Se	0.889	0.790	0.927	0.859	0.032	0.001	0.903	0.815

3.16.5 Blueberries

There are several species of blueberries in Sudbury. Two of the most common are *Vaccinium angustifolium* and *V. myrtilloides*. Blueberries are an important economic species and were selected as a valued ecosystem components (VEC) of the Sudbury ERA. However, blueberries were not explicitly evaluated as part of Objective #1. In addition, the Objective #1 studies concentrated on forest ecosystems, where as blueberries tend to thrive in more open areas, with little to no canopy cover, and moderate to low soil pH. As there are no standardized toxicity test protocols for blueberries, the direct effect of COC on blueberries could not be assessed.

3.16.6 Soil Characterization

There is a great deal of literature available which outlines typical soil chemistry parameter values in agricultural soils, however very little literature was found to pertain to northeastern Ontario forested soils. As a result, the SARA Group contacted a variety of groups and sources to try to determine whether the soil chemistry results collected at the test and reference sites could be considered representative of northeastern Ontario forested conditions. Researchers at Laurentian University were contracted to review the available grey and published literature and to contact groups that might have archived information for comparative purposes. This process revealed that there was no recognized classification of “normal” or “reference” conditions for soils in northeastern Ontario. The categories of high, medium and low quality soils were based upon a mixture of literature values, reference site conditions and the professional opinion of soil scientists familiar with the Sudbury region. The SARA Group acknowledges that the high quality soil values may or may not be representative of typical northeastern Ontario conditions on a regional basis. We feel confident, however, that the "high quality soil" values derived are representative of typical Sudbury sites where plant communities are established.

3.16.7 Plant Community Assessment LOE

Ecological integrity was defined and evaluated as part of the plant community LOE. This information was based upon information collected during the summer of 2004. Temporal aspects such as successional changes, seasonality and age structure are confounding factors, which make the interpretation of ecological integrity difficult and represent one area of uncertainty in the interpretation of the plant community LOE.

3.16.8 Invertebrate Toxicity Tests

For initial screening purposes, two species of invertebrates, *Eisenia. andrei* (earthworm) and *Folsomia candida* (collembolan), were chosen for inclusion in the soil toxicity test battery. *F. candida* was not sensitive to high levels of COC and was subsequently removed from the test battery. *E. andrei* was retained in the test battery as an indication of the toxicity of test site soils. The earthworms did not tolerate the natural site soils and did not reproduce at ambient pH regardless of metal level in the soil. Earthworms were only observed at 3 sites: CON-07, the historically limed and re-greened site (pH= 6.45 -6.75; Ni= 255 - 313 mg/kg; Cu= 170 - 240 mg/kg), FB-01 (pH= 3.21; Ni=422 - 535 mg/kg; Cu= 655-909 mg/kg), and REF-02 (pH= 3.59 - 4.03; Ni= 31.0 - 46 mg/kg; Cu= 40.7 - 42 mg/kg).

It is important to note that there are a very limited number of standardized toxicity tests for soil organisms, and there are no tests available for native Sudbury species. Furthermore, there are no indigenous species of earthworms in Ontario. In fact, all the earthworm species present in Ontario migrated into the area or were deliberately or accidentally introduced. However, the only suitable Canadian toxicity test method for soil invetebrates at the time of this study was for earthworms. This was a recognized uncertainty early in the process, but it was agreed that the most relevant approach taken would include toxicity tests with collembolans and earthworms.

3.16.9 Plant Toxicity Tests

Although the specific uncertainties for the Toxicity Testing LOE are discussed in the Toxicity Testing Ranking Report (Appendix GF-9), it should be noted that the species selected for the toxicity testing were not native species to the Sudbury area. The main reason for selecting "surrogate" test species was that standard toxicity test methods exist for these species. Unfortunately, the available standard methods did not include native species from the Sudbury area, or species specifically grown in northern boreal forests with naturally low soil pH. The development of standardized test species requires significant resources and extends beyond the scope of the ERA. For this reason, test species had to be chosen from those with developed standardized methods, and adapted for soils in the Sudbury region.

3.16.10 Split Rankings for Toxicity Testing LOE

There was considerable variability in the ability of the test species to perform in the soil from the various reference sites. Therefore, a mean of the values for each endpoint for the three reference sites was established and was referred to as REF_{mean}. Consequently, two approaches were used to evaluate the toxicity test data for the test sites:

- Approach 1: Compare toxicity test endpoint results using test site soil to each of the three reference sites.

- Approach 2: Compare toxicity test endpoint results using test site soil to the REF_{mean}.

The two approaches were considered together to give the overall ranking for the site. For two thirds of the sites (12 sites), the site ranks from the two approaches were in agreement. For the other sites, the ranks were split between moderately and severely impacted (four sites), and between not impacted and moderately impacted (one site). These split rankings indicate that the true rank for the site probably falls between the two. The use of two statistical approaches to evaluate the data increases the robustness of the toxicity testing LOE. A split ranking does not indicate uncertainty, but rather identifies a site that is between ranks.

3.16.11 Aluminum Toxicity

Aluminum is a major soil constituent, but it is not a plant nutrient. At low pH it can inhibit plant growth. Under acidic conditions ($pH < 5.5$) aluminum solubilizes and becomes readily available for plant uptake, creating a potentially toxic environment. However, under neutral or basic conditions ($pH \geq 7$) the metal precipitates and is no longer a threat to plant health. Given the low pH of soils in the Sudbury area it is possible that aluminum toxicity is contributing to the observed ecosystem impairment at the test sites. Both total and water leach (plant available, expressed in both µg/L and µg/g) aluminum concentrations were measured in soil cores from all 22 study sites (Table 3.67). Although it was considered for assessment, aluminum was not selected as a COC for the Sudbury ERA because it did not meet the selection criteria established by the TC (see Volume 1, Section 8). Therefore, aluminum can only be considered as a confounding factor and a source of uncertainty in the assessment.

Threshold soil concentrations for aluminum are not available. The US EPA (2003) was unable to establish an Ecological Soil Screening Level (ECO-SSL) for aluminum given the lack of available information for either total or soluble aluminum. An alternative screening procedure for aluminum was established, wherein aluminum is identified as a chemical of potential concern in those soils with a soil pH less than 5.5 (US EPA, 2003). Based on this threshold, there is some potential for ecological risk due to aluminum at all of the test and reference sites, with the exception of CON-07 (which has a pH greater than 5.5 due to historical liming).

Threshold aluminum concentrations in irrigation water and soil solution for the protection of crop plants are available (e.g., CCME (1999) and Environment Australia (2000)), but these are not directly comparable to either total or water leach aluminum concentrations in soil, and are applicable to crop plants, not the Northern forest species relevant to the Sudbury region.

The above information suggests that aluminum toxicity could be an issue in the Sudbury area due to low soil pH. The data also suggest that aluminum toxicity may be contributing to the impairment observed in the plant community, but to an unknown degree. This remains a confounding factor in the assessment.

Table 3.67 Total Aluminum, Water Leach Aluminum and pH in Soil Cores (0-5 cm) from 22 Study Sites

Site	pH[a]	Total Al (Microwave digest) (μg/g)[b]	Water Leach Al (μg/L)[c]	Water Leach Al (μg/g)[c,d]
CC-01	4.55	20,400	190	1.30
CC-02	4.19	12,200	171	1.17
CC-03	4.43	19,200	112	0.77
CC-04	4.81	14,700	263	1.80
CC-06	4.54	11,600	256	1.75
CC-07	4.58	13,000	243	1.66
CC-08	4.51	14,400	308	2.10
FB-01	4.1	9,200	258	1.76
FB-02	4.77	10,500	3,240	22.1
FB-03	4.24	14,200	294	2.01
FB-05	4.75	8,100	68	0.46
FB-06	4.37	11,500	3,830	26.2
CON-01	4.34	9,500	895	6.11
CON-02	4.41	14,500	157	1.07
CON-03	4.53	19,100	479	3.27
CON-05	4.39	32,900	312	2.13

Table 3.67 Total Aluminum, Water Leach Aluminum and pH in Soil Cores (0-5 cm) from 22 Study Sites

Site	pH[a]	Total Al (Microwave digest) (μg/g)[b]	Water Leach Al (μg/L)[c]	Water Leach Al (μg/g)[c,d]
CON-06	4.6	16,600	47	0.32
CON-07*	7.19	10,400	74,300	507.5
CON-08	4.5	18,100	8,760	59.8
REF-02	4.09	9,200	320	2.19
REF-03	4.88	25,000	220	1.50
REF-04	4.04	16,500	740	5.05

*CON-07 is the historically limed and re-greened site

[a] Analyzed by Testmark Laboratories, water slurry method by M.R. Carter, Ed., 1993

[b] Analyzed by Testmark Laboratories, method 3051 ICP-MS by SW846, method 6020, SW846

[c] Analyzed by Testmark Laboratories, analysis by ICP-MS by SW846, method 6020, SW846 and ICPOES APHA-3120

[d] Metal concentrations from water leach extraction were converted from units of μg/L to μg/g by multiplying by the standard volume (L) and dividing by the soil weight corrected for moisture (g). Soil moisture content was assumed to be 26.8%, and the soil mass used was assumed to be 20 g.

3.16.12 Colour Ranking Approach

The colour ranking approach used in this study was essentially a visual aid used to interpret a large quantity of combined data. Warren Hicks and Moore (1998) state that it is often desirable to combine sets of existing physical, chemical or biological data in order to develop a more comprehensive characterization of exposure or toxicity, and discuss some of the uncertainties associated with this process in ERA.

The approach to rank the 18 test sites involved the ranking of four individual lines of evidence (LOE), including associated influencing factors, and then applying a weight of evidence (WOE) approach to determine an overall ranking for each test site. Sites were ranked relative to reference sites by a colour code to indicate level of impact. Red signified a severely impacted site, yellow signified a moderately impacted site and green signified a site where little to no impact was determined. LOE were not all given equal weighting in the WOE approach. More weighting was given to the Plant Community Assessment and Toxicity Testing LOE, as compared to the Soil Characteristics and Decomposition LOE. The colour ranking system does not provide quantitative or numeric values to determine overall ranking, which results in some uncertainty with regard to precision of the final site rank.

The SARA group understands that a numeric system could have been used, but felt that the numeric designation implies more precision than was considered appropriate. The WOE stepwise process used here provides decision makers with all the pertinent information necessary for risk management. The

SARA Group feels that the colour ranking system employed is supported by the necessary data. Sudbury is a large area with many confounding factors that influence toxicity and impact; the simplicity of the colour ranking system provides an overall process to categorize risk. It was never assumed that risk managers would treat all "red" sites the same. Rather the delineation of a severely impacted ranking (red), enables risk managers to prioritize sites, categorize remediation strategies, and identify a areas that could be addressed.

The site rankings will be extrapolated to the larger study to help identify the general areas at risk. The areas predicted to be at risk need to be verified through ground-truthing and supplemental data collection (see Chapter 6). Therefore, there should be very low probability of making the wrong risk management decision due to uncertainty with the ranking system.

3.16.13 Sample Size and Statistical Power

This study was designed to evaluate a large number of parameters at a relatively small number of study sites (18 test sites, 1 historically limed and regreened site and 3 reference sites). This design facilitated the detailed and comprehensive comparisons of the test to reference sites that were used to determine the level of impact at each site. Uncertainty in the assigned impact rankings was minimized through the use of multiple lines of evidence, each consisting of multiple parameters, which could not have been achieved using a study design that measured fewer parameters at a larger number of sites.

Additional statistical analyses were conducted to examine possible relationships between various parameters and metal concentrations. However, the original study was not designed to undertake these statistical analyses. For example, analyses were conducted to identify correlations between extractable metal levels in site soils and toxicological responses of test organisms to site soils. These analyses were conducted separately for the individual transects, or using the entire dataset, as appropriate. Extensive statistical analysis of the data did not reveal any relationships stronger than those discussed in the report. The statistical power of these analyses was low due to the natural variability in the data and the sample size. The lack of power in these analyses means that relationships may be present in the natural environment that could not be detected using the data collected.

3.16.14 Causal Analysis

Causal analysis is a process in which data and information are organized and evaluated using quantitative and logical techniques to determine the likely cause of an observed condition (U.S. EPA, 2000). Causality is evaluated using a formal set of criteria based on Hill (1966) and others. The causal criteria most often used related to environmental impacts include (U.S. EPA, 2000; Hull and Swanson, 2006):

- **Spatial correlation**: Effects occur at the same place as exposure; effects do not occur wherethere is no exposure.
- **Temporal correlation**: Effects occur with or after exposure.
- **Biological gradient/strength**: Effects decline as exposure declines in the landscape. Similarly, effects decline as exposure declines over time (or effects increase as exposure increases over time).
- **Plausibility (mechanism):** It must be known how the stressor causes an effect in the affected organisms. This will determine whether it is plausible that the observed effects are a result of the stressor.
- **Plausibility (stressor-response)**: The magnitude of effect is expected based on the level ofthe stressor.
- **Consistency of stressor/effect association**: Repeated observation of effect and stressor in different studies or different locations within the region being studied. In addition, there is existing knowledge from other regions where similar (analogous) stressors have caused similar effects.
- **Experimental verification**: Effects of the stressor are observed under controlled conditions and there is concordance of these experimental results with field data.
- **Specificity of cause:** The tendency for the effect to be associated with exposure to a particular stressor. Effects should be defined as specifically as possible to increase the specificity of the association between cause and effect. In the extreme case, causation is clear when a stressor results in only one effect, and that effect is only related to that one stressor. Of course, this is rare in environmental situations

A causal analysis is simplest to complete when the candidate causes result in different effects, or different magnitudes of effects. Causation also is facilitated when experimentation can differentiate between candidate causes. In the case of the Sudbury ERA, the candidate causes of impacts to plants include the following:

- Metals in soil
- Low soil pH
- Previous exposure to SO_2
- Low soil nutrient levels
- Low soil organic matter levels
- Changes in metal bioavailability resulting from pH, Ca^{2+}, and other modifying factors

It is not possible to differentiate between many of the candidate causes. It is particularly difficult to differentiate causes because many met the same causal criteria (e.g., spatial correlation, temporal correlation, plausible mechanism), and experimentation was not able to separate the candidate causes (Section 3.13). Therefore, a full causal analysis, such as is recommended by U.S. EPA (2000) and Hull and Swanson (2006) is not possible. However, the results of the studies conducted for Sudbury did provide valuable insight (Section 3.13).

The Objective #1 study data suggested that impact to plant survival and or growth in laboratory toxicity tests could be related to either soil pH, metal concentrations, lack of organic matter and nutrients, distance from smelters, interaction of soil pH and metal concentrations or the interaction of multiple variables. The use of multiple lines of evidence in a weight of evidence approach was taken to reduce the uncertainty associated with a single line of evidence. Due to the limitations of scientific knowledge and understanding of the diversity, complexity and variable interactions in nature, only a partial causality analysis could be completed (Section 3.13); as inferred from the integration of multiple lines of evidence.

3.16.15 Other Confounding Factors

- Deforestation (from logging, forest fires and SO_2 deposition) is another historic factor responsible in part for the status of the present terrestrial community in Sudbury. While it cannot be definitively quantified, deforestation must also be taken into consideration when determining the causal factors of impact.

- Soil loss due to erosion. Extensive soil loss as a result of the loss of vegetation cover has impeded vegetation recovery in the Sudbury area. This mass scale erosion has resulted in the loss of organic matter and the crucial topsoil layers that supply the medium for plant growth; leaving areas with either exposed rock or relic soil layers that are deficient in nutrients and organic matter. Soil COC concentrations along the Coniston transect, tend to be below what is typically considered for impacted areas due to the fact that the deposited metals were washed away along with the top layers of soil.

- Metal toxicity is strongly influenced by pH. In particular, low pH increases the bioavailability (and hence toxicity) of cationic metals. Sudbury area soils are known to have low pH, as evidenced by the results of the 2001 Regional Soil Study, which indicated that many areas in the Sudbury region had soil pH levels less than 5. While some areas of low pH soils can be directly associated with the SO_2 deposition, the 2001 Study found that the lowest soil pH levels were not in regions where SO_2 deposition was traditionally the highest. Therefore, low pH is a natural characteristic of the region, and must be taken into consideration when determining soil toxicity and causal relationships.

3.17 Summary and Conclusions

Objective #1 was addressed using a weight-of-evidence approach. To achieve this, detailed data and samples for each LOE were gathered from 22 study sites (18 test sites, one historically limed site and three reference sites) across the Sudbury area during an intensive field and laboratory program conducted during 2004 and 2005. The “test” sites represented locations containing a range of soil metal concentrations and conditions along transects associated with the three smelters: Copper Cliff, Falconbridge and Coniston. Three reference sites were selected for comparative purposes where the concentrations of COC were below the MOE Table “F” background criteria levels (MOE, 1997) and the sites were representative of northeastern Ontario forest community conditions. The total metal concentrations and the pH of the soil were the primary factors used to guide site selection. The test and reference sites for this study were selected to ensure a pH range of between 4.0 and 5.0 in the 0-5 cm mineral soil depth in an attempt to minimize the potential impact of pH variability in the evaluation.

A considerable amount of effort was devoted to the study design for this Objective and selection of test and reference sites. The sampling locations were reflective of the distribution and concentration of COC in the Greater Sudbury study area.

The LOE collected were as follows:

- physical and chemical soil characterization;
- toxicity testing with single terrestrial species in the laboratory;
- a plant community assessment; and
- an assessment of decomposition using *in situ* litter bags.

The process of data evaluation and integration followed a three-step procedure. In Step 1, each of these LOE was evaluated independently to categorize the relative level of impact at each site irrespective of soil metal levels. In Step 2, the interactions between the LOE were evaluated using statistical techniques. Finally, in Step 3, the LOE were integrated using a WOE approach to determine whether the concentrations of metals in the soil were likely impeding recovery of a self-sustaining forest system.

In Step 1 the test sites were ranked for each LOE, and then given a final rank without considering soil metal content. Eight of the 18 test sites were ranked as moderately impacted with the other 10 test sites ranked as severely impacted relative to the reference sites.

During Step 2, interactions between chemistry parameters in the site soil and the toxicity test results and plant community LOE were assessed. Two statistical approaches were applied to the data from the various LOE to determine whether relationships existed between the soil chemistry parameters and the toxicity testing results or between the chemistry parameters and the plant community. These analyses showed that, based on data from the 22 sites, the level of COC in the soil was related to toxicity to plant species in the laboratory, and to the structure of the plant communities in the study area. Soil fertility. Such as level of Mn and Ca, was also identified as a factor of importance.

During Step 3, the sites were given a final ranking in conjunction with the metal levels (total and water leach) and distance from the smelter along each transect. The sites were qualitatively evaluated to determine whether the concentration of COC could reasonably be considered to contribute to the relative impacts at the test sites. The Step 3 evaluation strongly suggests that the COC in the Sudbury region are contributing to the impeded recovery of a self-sustaining plant community. Other factors that were also identified as important are soil fertility, soil pH, incidence of forest fires in the past, the concentration of Ca and organic matter in the soil.

The role of soil pH as a confounding factor in this study was examined by conducting soil toxicity tests in natural (low pH) and pH-amended soils, as well as collecting and comparing detailed field measurements from a historically limed site and an adjacent site that was not limed. These studies showed that low soil pH can impact plant growth directly, as well as interact with soil metals to contribute to soil toxicity. The post liming and regreening activities have helped to establish a diverse plant community with the introduction of essential minerals (Cs, Mg) and a viable see source. Based on the analysis results the bioavailable fraction of COC appeared to be higher at the unlimed site. Because soil pH influences metal speciation and bioavailability, it is not possible to totally separate the relative role of pH from metal toxicity.

The results of the extensive studies carried out to evaluate Objective #1 indicated that the concentration of COC have in the past impacted the plant communities, and are likely continuing to impede the recovery of a self-sustaining forest community in the Sudbury region. However, other environmental variables and soil conditions are also contributing to inhibiting ecosystem recovery and all these factors are intertwined to the extent that it is not possible or practical to isolate their roles over a large landscape. The implications of these findings are discussed further in Chapter 6.

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