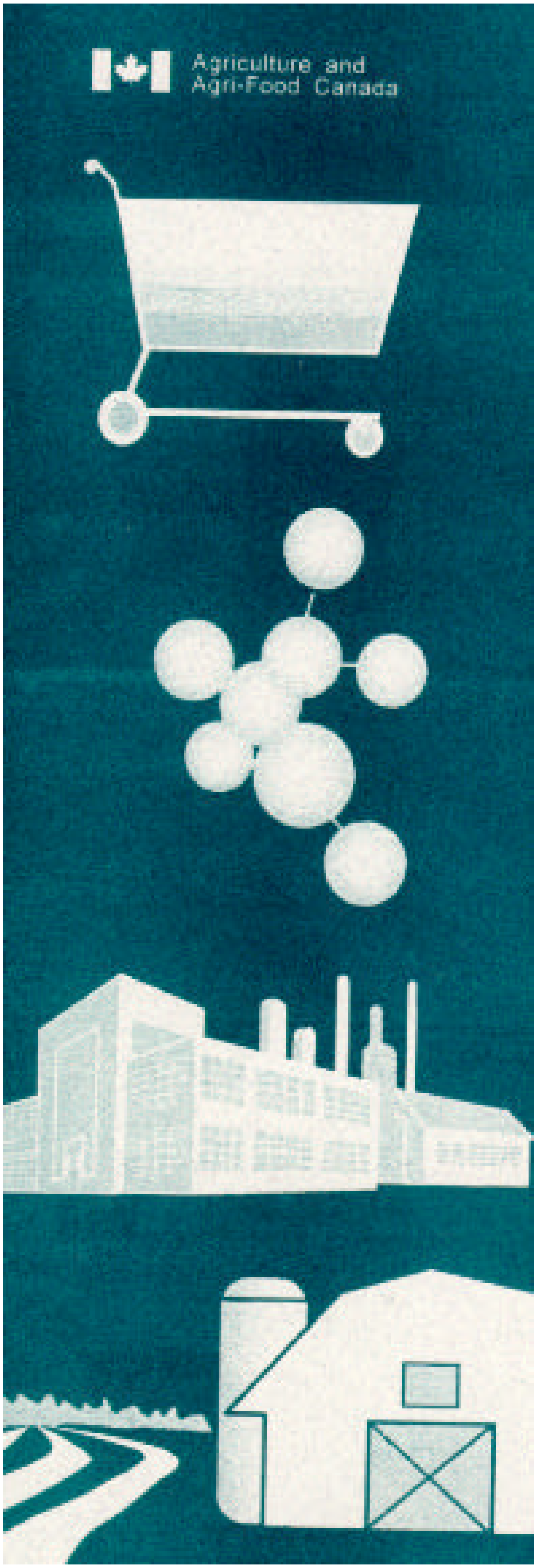

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Status of Selected Trace Elements in Agricultural Soils of Southern Manitoba

April, 1998

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EXECUTIVE SUMMARY

Introduction

This report provides documentation of the status of trace elements in soils of southern Manitoba. Information on the content and distribution of selected trace elements in soil is important for several reasons:

- to characterize and assess soil quality and health,
- to evaluate soil quality for crop growth and forage and livestock production,
- to determine safe levels for application of sewage sludge and effluent and management of livestock waste for enhanced crop production,
- to ensure that all crop production and waste management practices are environmentally sustainable and consistent with the protection of the soil and water resource,
- to provide baseline information required to determine the environmental impact from accidental chemical spills and assess the risk of environmental contamination.

Methodology

Soil samples were collected from 121 soil landscapes within the agricultural area of Manitoba. The Soil Landscapes Map for Manitoba was used to stratify the sampling procedure and to portray the distribution and concentration of individual trace elements. A series of thirteen metals, a semi-metal and one non-metal that commonly occur in the environment in trace amounts are monitored in this study.

Trace Elements in the Environment

Trace elements are released into the environment from the natural weathering of rocks and minerals and from various sources related to human activity. Although the concentration of these elements occurring in nature is generally low, they may directly or indirectly affect the chemical composition of foodstuff and animal feed, potable water supplies and airborne particulates and dust. The practical implication of trace elements in the environment relates to their availability for plant uptake from the soils and their release into water systems. The content of trace elements in soil is an indication of possible excesses or deficiencies for plant nutrition and ultimately animal and human health. The data in this study indicate the total concentration of selected trace elements in soil and as such are an indication of potential problems of excess or deficiency. The amounts of trace elements which are bio- or phytoavailable will be lower. Contamination of the environment is generally associated with the quantities that are added to the soil or water from man-made sources such as industrial discharge and volatile emissions, sewage sludge, livestock wastes and other wastes.

Factors Affecting the Concentration and Distribution of Trace Elements in Soil

The wide range in concentrations of trace elements observed in the soil and water environment is the result of interaction between various factors affecting geological weathering and soil forming processes:

- mineralogical and chemical characteristics of bedrock,
- soil texture (amounts of sand, silt and clay),
- the effect of glaciation in eroding bedrock material and in the transport and deposition surficial deposits and soil parent materials,

- local soil and hydrological conditions affecting processes of soil formation, soil development and availability of trace elements for plant uptake or concentration in surface or ground water.

Concentration and Distribution of Trace Elements in Manitoba Soils

- The regional distribution of most trace elements in Manitoba soils shows a strong relationship with soil texture. Soil materials high in clay have the greatest concentration in all analysed elements.
- Soils formed on parent material high in Cretaceous shale are highest in the majority of trace elements.
- Elevated concentrations of trace elements in soil usually reflect a direct bedrock influence.

Summary

- The data from this study provide preliminary background levels for selected trace elements in Manitoba soils.
- Levels of trace elements studied are generally within the range for soils in the Interior Plains of western Canada and also within the range for soils on a world-wide basis.
- Selenium and molybdenum were found to occur in some Manitoba soils in amounts exceeding the higher end of the world scale and the highest level of vanadium found in Manitoba soils is at the upper end of the world range in soil vanadium content.
- Trace elements examined in this study that are potentially toxic to biological systems and therefore of environmental concern are within reported levels of acceptability.
- Background concentrations of trace elements in agricultural soils provide a baseline value for assessing potential loading capacity for application of sewage sludge, animal wastes and other materials containing trace elements to soil.
- The application to agricultural soils is a beneficial method of managing sewage sludge and effluent and animal waste. However, addition of contaminants to soil in these and other waste materials must be monitored and controlled in order for such practices to be sustainable and protect the soil and water resource in the environment.

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ACKNOWLEDGEMENTS

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TRACE ELEMENT STATUS OF AGRICULTURAL SOILS IN SOUTHERN MANITOBA

INTRODUCTION

This study was initiated in 1985 in response to the increased interest in the background levels of selected trace elements occurring in the agricultural soils of southern Manitoba. A series of thirteen metals, a semi-metal (As) and a nonmetal (Se) that commonly occur in the environment in trace amounts were monitored for this study. The importance attached to the trace element content of soil is in response to scientific and public awareness and concern for environmental issues related to soil and water quality. In addition, analytical techniques are now available for detecting very small quantities of these elements.

Information on background levels and distribution of trace elements in Manitoba soils is important for environmental assessments and the need to respond to public concern about the impacts of accidental chemical spills and risk of environmental contamination. Such information is also required to evaluate soil quality for crop growth, forage and livestock production as well as for the safe level of sewage sludge and effluent disposal. The data presented in this study are derived from "total" and "near-total" analyses for each element and the amounts reported are maximal amounts. The phyto- and bioavailable amounts, which are governed by such factors as soil pH, oxidation conditions and organic matter content, will be lower.

The utilization of agricultural land for disposal of municipal sewage sludge and effluent is generally recognized as an environmentally acceptable practice (Webber and Shamess, 1987). The management of agricultural wastes through application to land focuses on its use as a resource to enhance or sustain soil quality and productivity rather than as a waste product for disposal.

Trace elements are released into the environment from the natural weathering of rocks and minerals and from various sources related to human activity. Although the concentration of these elements occurring naturally in the environment is generally small, they may directly or indirectly affect the chemical composition of foodstuff and animal feed, potable water supplies and airborne particulates and dust (Singh and Steinnes, 1994). The practical implication of these trace elements in the environment relates to their availability for plant uptake from the soil and their release into water systems. Contamination of the environment by trace elements is generally related to the quantities that are added to the soil or water from man-made sources such as industrial discharge and volatile emissions, sewage sludge, livestock manures and other wastes.

The content of trace elements in soil is an indicator of possible excesses or deficiencies for plant nutrition and ultimately animal and human health (Dudas and Pawluk, 1977; Boila et al., 1984, 1985; Kruger et al.,1985; Gupta, 1986). Research has been conducted on the effects of sewage sludge application on agricultural land and on plant uptake of trace elements (Zwarich and Mills, 1979; Webber and Shamess, 1987). However, limited information is available on background levels of trace elements in Manitoba soils (Haluschak and Russell, 1971; Madden, 1974; Mills and Zwarich, 1975). In consideration of the ever increasing pressure being placed on land by more intensive land management practices and the increasing use of agricultural land for waste management, it is important to document the trace element status of Manitoba soils. Information of this kind is required to adequately address issues related to plant and animal nutrition, food safety and quality of the environment. Growing public concern for sustainability of Manitoba's soil and water resources serves to reinforce this need.

OBJECTIVES

This study was undertaken to provide a general assessment of the background levels of trace elements in a wide range of agricultural soils in southern Manitoba. The specific objectives of this study were to:

1) assess background levels of trace elements in major agricultural soils, and
2) determine the geographic distribution of selected trace element concentrations in soils of southern Manitoba.

OUTLINE OF THE REPORT

The concentration and distribution of trace elements in soils is closely related to the nature of the parent rocks and minerals from which the soil was derived. Therefore, before undertaking an evaluation of each element, a brief overview of relevant aspects of bedrock geology, physiography, surficial geology and glacial history is presented. These have all influenced the composition and distribution of soil parent materials and so aid in the interpretation of the data and assist in its extrapolation to the Manitoba landscape.

The general soil landscape attributes utilized for extrapolation of the distribution and concentration of individual elements are portrayed on a soil landscape basis. The Soil Landscapes of Canada map at a 1:1 000 000 scale (Canada Soil Inventory, 1989) was used as a basis for stratifying the sampling procedure and thus was also used as the base map for displaying the data for individual elements. The reader is encouraged to obtain a copy of the Soil Landscapes of Canada map to use in the discussion section of this report.

PHYSICAL ENVIRONMENT OF SOUTHERN MANITOBA

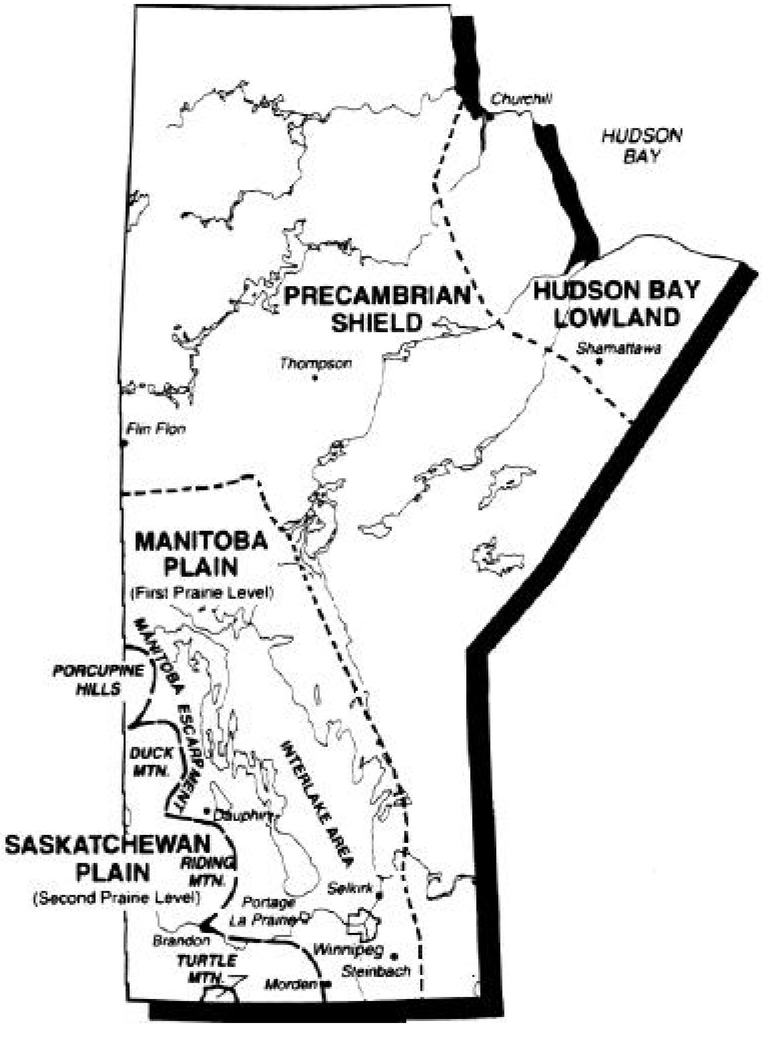
Knowledge of the physical environment, ie., physiography, bedrock formations and surface deposits, as well as an understanding of the glacial history is important for characterizing the distribution of trace elements in soil. Data about the chemical and mineralogical properties of different bedrock types provides information concerning the source of these elements in soil. The effect of glaciation on shaping the land surface and on distributing surface deposits helps in extrapolating the point data obtained in this study to the landscape.

The distribution of trace elements in the agricultural soils of southern Manitoba is directly influenced by a number of factors:

- the mineralogical, chemical and physical properties of the various bedrock formations,
- the mineralogical, chemical and physical characteristics of the surface deposits resulting from erosion and deposition by continental glaciation and
- characteristics of the soil derived from weathering of the various surface deposits.

Physiography

Southern Manitoba extends across two major physiographic regions: the **Shield** consisting of a central core of ancient Precambrian crystalline rocks to the north and east and younger sedimentary rocks of the **Borderlands** to the south and west (Bostock, 1970). The Borderlands covers all of south-central and southwestern Manitoba and is divided into the Manitoba Plain adjacent to the Shield and the Saskatchewan Plain further to the west (Figure 1). The boundary between the Manitoba Plain and the Saskatchewan Plain is clearly marked by the Manitoba Escarpment, which was formed in part by underlying strata of Cretaceous shale bedrock. Outcroppings of the Upper Cretaceous shales along this Escarpment are important trace element sources to soils in southwest Manitoba. It also marks the boundary between the younger, very high carbonate soil materials derived from Paleozoic limestones and dolostones, and the less calcareous soil materials of mixed lithology in southwest Manitoba.



Shield Region
Precambrian Shield
Hudson Bay Lowland

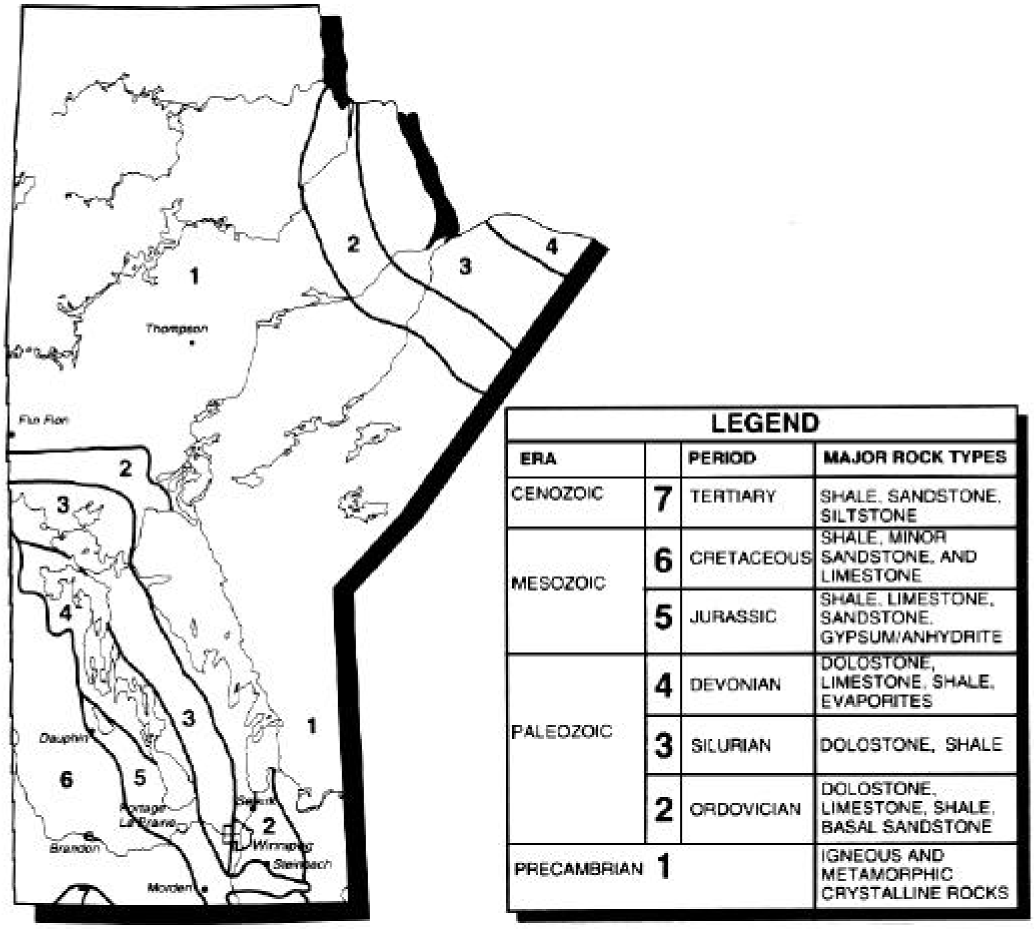
Borderlands (Interior Plains)
Manitoba Plain
Saskatchewan Plain

Figure 1. Physiographic regions of Manitoba

Bedrock Geology

The bedrock of Manitoba consists of a central Precambrian Shield region of ancient igneous, volcanic and metamorphic rock covering some 60 percent of the province. The Shield outcrops from the southeastern corner of Manitoba through to the northwestern corner of the province. The Precambrian rock is overlain by younger, flat-lying sedimentary rock in the two large depositional basins occupying the southwestern and northeastern parts of the province (Figure 2).

These sedimentary rock formations are subdivided into the Paleozoic, Mesozoic and Cenozoic eras based on age. In south-central and southwestern Manitoba, the oldest Paleozoic rocks lie directly on the Shield and consist of layer upon layer of carbonate rocks, mainly dolomite, although interbedded shales and sandstones are present. The younger Mesozoic rocks, predominantly shales with lesser amounts of sandstones, carbonates and evaporites, overlap the Paleozoic rocks. Cenozoic rocks, the youngest rock formation in Manitoba, are found only in the extreme southwest portion of Manitoba, overlying the Mesozoic rock on Turtle Mountain. These rocks are of Tertiary age and consist primarily of shales and minor sandstone, siltstone and lignite.



LEGEND

ERA		PERIOD	MAJOR ROCK TYPES
CENOZOIC	7	TERTIARY	SHALE, SANDSTONE, SILTSTONE
MESOZOIC	6	CRETACEOUS	SHALE, MINOR SANDSTONE, AND LIMESTONE
	5	JURASSIC	SHALE, LIMESTONE, SANDSTONE, GYPSUM/ANHYDRITE
PALEOZOIC	4	DEVONIAN	DOLOSTONE, LIMESTONE, SHALE, EVAPORITES
	3	SILURIAN	DOLOSTONE, SHALE
	2	ORDOVICIAN	DOLOSTONE, LIMESTONE, SHALE, BASAL SANDSTONE
PRECAMBRIAN	1		IGNEOUS AND METAMORPHIC CRYSTALLINE ROCKS

Figure 2. Generalized bedrock geology of Manitoba

Surficial Geology

The bedrock in southern Manitoba is covered almost entirely by varying thicknesses of unconsolidated surface deposits resulting from glaciation and deposition of glacial sediments, including tills, glaciofluvial and glaciolacustrine materials during and following deglaciation some 8 000 years ago. The physical and chemical properties of these materials are determined by the mineralogical and chemical composition of the igneous, carbonate and shale bedrock, the three rock types most likely to have been incorporated into the surface deposits. These rock materials weather over time to become the parent material for soil and ultimately determine the trace element composition of the soil.

I) Glacial Till

The most extensive surface materials in southern Manitoba are glacial tills, derived from bedrock materials that were ground up by glacial ice movement. Glacial till occurs as moderately calcareous, loamy, moderately stony to near stone-free material in the Saskatchewan Plain, as highly calcareous, loamy, very stony material in northern parts of the Manitoba Plain and as sandy, acidic, excessively stony material on the Precambrian Shield. Till deposits in the Saskatchewan Plain are derived from a mixture of shale, carbonate and granitic rock materials. The lithologic composition of these materials varies from mixtures of carbonates, granitic and shale materials to till derived predominantly from ground-up shale. Highly calcareous till in the Manitoba Plain is derived predominantly from ground-up limestone and dolostone in which shale is absent although varying proportions of granitic materials are included. The acidic till in the Precambrian Shield is derived from granitic and volcanic bedrock.

ii) Lacustrine Sediments

Materials initially deposited in glacial lakes form the next most common surficial material in southern Manitoba. These deposits, referred to as lacustrine sediments, consist of either stratified fine sand, silt and clay deposited in quiet, deep waters as lake beds or moderately well sorted and stratified sand and coarser materials such as beach and near-shore sediments transported and deposited by wave action. Major areas of lacustrine sediments occurred in glacial Lake Agassiz as silt and clay deposits in the southern portion of the Manitoba Plain. In this environment sediments are thick (in excess of 15 m) and continuous in the south but thinner and discontinuous in areas to the north. The clay sediments originated from erosion of the Cretaceous shale bedrock along the Escarpment and as outwash from the mixed till of the Saskatchewan Plain. Sandy and loamy sediments in the west were laid down in smaller glacial lakes in southwest Manitoba and local areas of clay material were deposited as supra-glacial sediments in contact with disintegrating ice on upland areas.

iii) Fluvial Materials

Other surface materials in southern Manitoba consist of fluvial, alluvial, aeolian and organic deposits. Local areas of fluvial materials deposited by flowing water, referred to as outwash, are generally stratified and moderately well sorted. Outwash materials consist mainly of rounded gravels mixed with sand and sometimes with minor amounts of silt. Such deposits usually occur at the upper portion of major deltas or within large meltwater channels.

iv) Recent Alluvial Sediments

Recent alluvial sediments are generally variable, stratified sand, silt and clay layers often interspersed with layers of buried organic matter. These sediments are deposited on flood plains associated with the Assiniboine or Saskatchewan Rivers or on the many small deltas along the Manitoba Escarpment. The vertical stratification or layering of the materials results from periodic accumulation of fresh materials on the surface of these landscapes during times of flood.

v) Aeolian Deposits

Wind blown materials are referred to as aeolian deposits. Aeolian materials usually consist of well sorted, poorly compacted, medium to fine sand and coarse silt. The characteristic duned topography associated with these materials results from modification of sandy and silty deltaic and lacustrine materials. Active and inactive sand dunes are evident on the surface of the Assiniboine Delta in the Carberry sandhills.

Soil Parent Materials

Surficial deposits resulting from geologic processes are the parent material from which soils develop. The physical, chemical and mineralogical characteristics of soil are a result of weathering of soil parent material over time. Weathering during soil formation results in physical disintegration and chemical decomposition of minerals and the release of metals from the parent material to the soil and to solution in soil water and ground water. A close relationship between the metal content of the parent material and soils that develop during weathering has been observed in a number of studies (Singh and Steinnes, 1994).

Soil formation results in specific soil types, the generalized distribution of which is shown on the Soil Landscapes of Canada - Manitoba map at a 1:1 000 000 scale (Canada Soil Inventory, 1989). Because this map shows the distribution of soil parent materials as well as the influence of soil formation on the various materials, it provides a suitable basis for assessing background levels of trace elements in the agricultural soils of southern Manitoba.

Mineralogy and Chemistry of Major Bedrock Types

The trace elements in soils result from the weathering of the rocks and minerals which are present in the soil parent material and originate from different bedrock types. Most metals in rocks and minerals occur in trace amounts, in contrast to elements such as silicon, aluminum, calcium, magnesium and iron that are dominant in the earth's crust as well as in the mineral fabric of soil.

Different bedrock types differ markedly in chemical composition. The concentrations of trace elements in soil parent material also vary according to the nature of the rock material that is incorporated into the mineral component of the soil. Although most of the trace elements are represented in most bedrock types, the concentration of individual elements often varies by orders of magnitude between different rock types (Taylor, 1964). The average geochemical background data for portions of the earth's crust and specific igneous and sedimentary rocks in Manitoba are summarized in Table 1 (Garrett, 1998).

Table 1. Compilation of average geochemical background data for the earth's crust and selected rock types *

		Si %	Al %	Hg ppb	Pb ppm	Cd ppm	Cr ppm	Ni ppm	As ppm	Cu ppm	Zn ppm
Earth's Crust											
	-1	28.1	8.2	80	13	0.2	100	75	2	55	70
	-2	27	8.3	90	12	0.2	110	89	2	63	94
Upper Continental Crust											
	-3	30.8	8	-	20	0.1	35	20	1.5	25	71
	-2	29.4	8.3	80	13	0.2	77	61	1.7	50	81
Igneous Rocks											
Ultramafic	**-4**	20.5	2	-	1	0.1	1600	2000	1	10	50
Mafic	**-4**	23	7.8	90	6	0.2	170	130	2	87	105
Intermediate	**-4**	31.4	8.2	80	15	0.1	22	15	2	30	60
	-3	27.1	9.5	-	10	-	55	30	-	60	-
Felsic	**-4**	34.7	7.2	80	19	0.1	4	5	1	10	39
Sedimentary Rocks											
Sandstone	**-5**	35.9	3.2	57	14	0	120	3	1	15	16
Limestone	**-5**	0	0.9	46	16	0.1	7	13	2	4	16
Shale	**-5**	26	8	270	80	0.2	423	29	9	45	130
Black Shale	**-6**	-	-	-	15	4	18	68	22	50	189
	-7	-	-	-	100	-	700	300	-	200	1500

1. Taylor, 1964.
2. Yee Tan and Yao Chi-Lung, 1970.
3. McLennan, 1992.
4. Turekian and Wedepohl, 1961.
5. Faust and Aly, 1981.
6. Dunn, 1990.
7. Vine and Tourtelot, 1970.

*(Garrett, 1998)

METHODOLOGY

The sampling intensity varied; at least one sample site and up to 25 sample sites were obtained from each of 121 areas portrayed on the Soil Landscapes of Canada - Manitoba 1:1 000 000 scale map (Canada Soil Inventory, 1989). The distribution and frequency of sample sites is shown in Figure 3. Large, relatively homogenous soil landscapes are reasonably well characterized by this sampling density. It should be noted however, that in applying this database to a wide range of landscapes, a sampling density that adequately characterizes a relatively homogenous landscape is not necessarily adequate to describe landscapes with greater inherent natural variability. In other words, the adequacy of the sampling program is not equal for all landscapes because landscapes are not always uniform; areas with greater soil variability would require additional sampling to more adequately characterize the full range of soils occurring within the landscape.

Soil samples were collected from the 0-15 cm depth (approximately the A horizon) and the C horizon (parent material sample from approximately the 50-60 cm depth). Additional samples collected from detailed soil inventory projects were selected to increase the sampling density in some landscapes. The soil series identified at each sample site was confirmed by field examination, physical and chemical analysis and verification from the soil map.

Precautions were taken to avoid contamination of samples during collection, preparation and analysis (some of the additional soil inventory project samples may have come into contact with metallic shovels, but the trace element concentrations of these samples do not appear to be elevated over other samples, so contamination, if any, was minimal). Samples were analysed for particle size distribution, pH, organic carbon and $CaCO_3$ content by standard methods (Carter, 1993). Particle size was determined by the sieve and pipette method with a pretreatment of hydrogen peroxide to remove organic matter. Readily oxidized organic carbon was measured by dichromate digestion. Soil pH was measured in a 15-g soil/30 ml 0.01M $CaCl_2$ mixture after stirring periodically for 1 hour. Determination of $CaCO_3$ was made using a pressure calcimeter.

Chemical analysis was carried out on a 20-g sample, air dried and finely ground with an agate mortar and pestle. A 1-g subsample was decomposed with a HF-$HClO_4$-HNO_3 mixture followed by atomic absorption spectrophotometry for arsenic, cadmium, chromium, cobalt, copper, iron, lead, manganese, mercury, molybdenum, nickel, selenium, silver, vanadium and zinc. The concentrations of elements in some samples were below the detection limits for cadmium, selenium and silver (all 0.2 ppm), molybdenum (2 ppm), and mercury (10 ppb). Data from these samples were included in the statistical analysis by reporting the results for each element as one-half of the detection limit for that element; these values were then used for all statistical evaluations, and are reported in the tables in the Appendix.

Data was summarized (Table 1, pg 7) and analysed with a dBASE STATS^{TM}(SPSS Inc. 1989) software package. The trace element characteristics are presented for individual soil series (Table 6, pg 57), providing another means of extrapolating data to the landscape.

Trace Element Study

Frequency and Distribution of Sampling Sites per Polygon

Scale 1:3 000 000

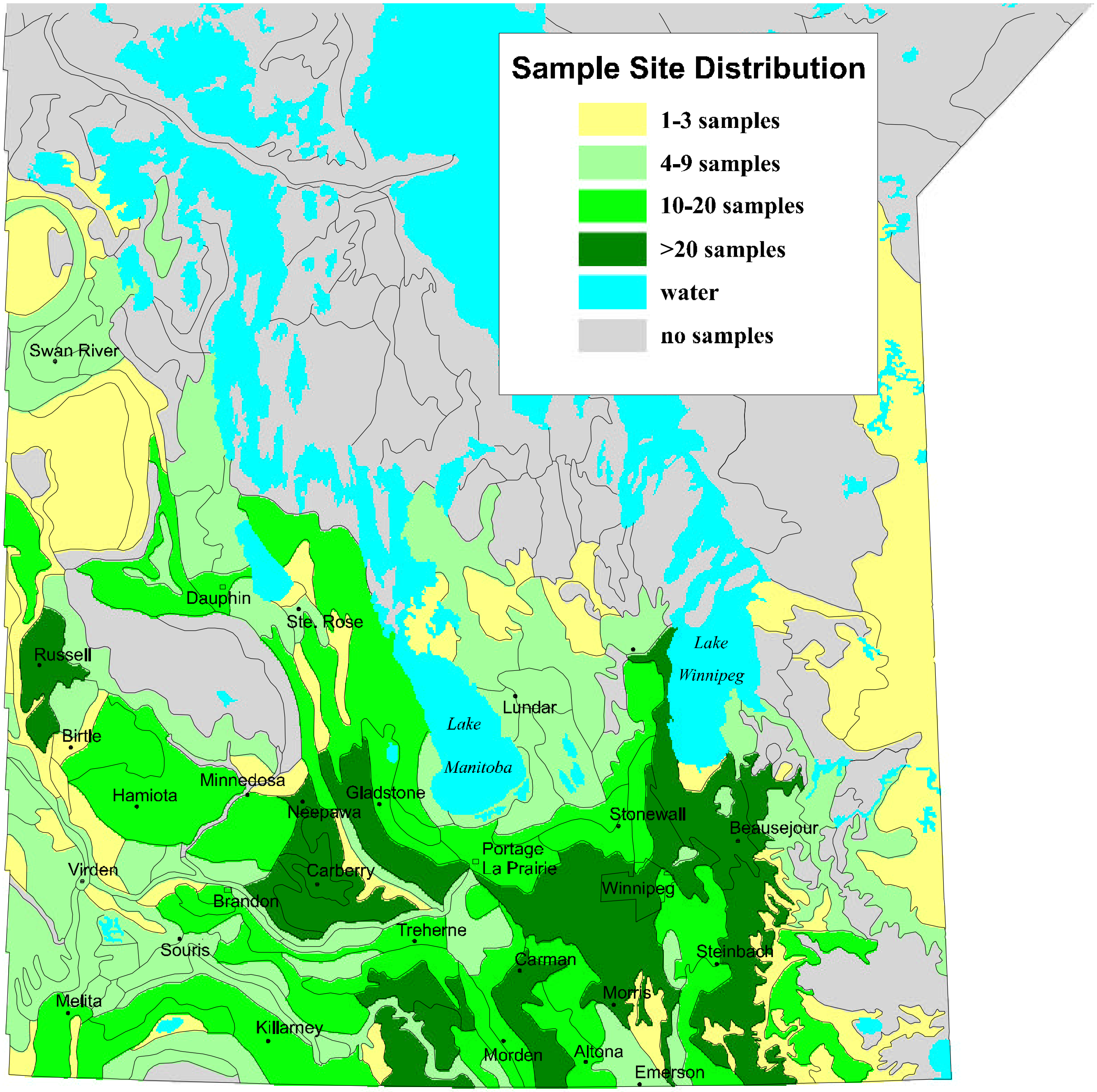


Figure 3. Frequency and distribution of sampling sites.

RESULTS AND DISCUSSION

Data Interpretation

The interpretation of the trace element data obtained in this study focuses on providing an overview of the content of selected elements and their distribution in soil landscapes of southern Manitoba. Difficulty in extrapolation of results from point data to the landscape often arises from lithologic differences within single parent materials. Additional problems in predicting the distribution of elements result from variability in provenance and/or selective mobilization and redeposition of individual elements during weathering processes (Webb and Howarth, 1979).

The concentrations of trace elements in agricultural soils in southern Manitoba are summarized for all samples, regardless of kind of parent material or soil texture in Table 2 (pg 4747). The relationship between the content of individual elements and soil texture is summarized in Table 3 (pg 48) and for broad textural groups in Table 4 (pg 50). The geographic distribution of the trace elements is shown on small-scale soil maps derived from the Soil Landscapes of Canada - Manitoba map (Canada Soil Inventory, 1989) at a scale of 1:3 000 000. The trace element contents in soils of southern Manitoba are also summarized according to soil landscape polygon (Table 5, pg 51) and by soil series (Table 6, pg 57) in the Appendix.

Total Content of Trace Elements

The summary statistics on the concentrations of the individual elements in the soils of southern Manitoba are shown in Table 2 (pg 47) which also includes values determined for soils of the Interior Plains (McKeague et al., 1979). For comparison purposes, these data can be related to values for crustal abundance and average values for the three rock types common to southern Manitoba, namely igneous, limestone and shale, as presented in Table 1 (pg 7).

The regional distribution of most elements within the parent materials in southern Manitoba shows a strong relationship with the actual texture of the material (Table 4, pg 50). Soil materials high in clay were highest in all analysed elements. In addition, parent materials high in Cretaceous bedrock were highest for the majority of trace elements. This is related to the enrichment of marine sediments with trace elements (Speirs et al., 1989).

A comparison between the analyses of soils in southern Manitoba and soils of the Interior Plains (Table 2, pg 47) indicates that the mean trace element levels of the Manitoba soils fall within the range reported for soils in the Interior Plains (McKeague et al., 1979). Mean levels obtained for Co, Cu and Hg are slightly below values reported for the soils of the Interior Plains, while mean levels for Cr, Ni, Pb, Se and Zn are slightly greater. The mean value obtained for Mn for soils of southern Manitoba exceeds the mean concentration on a regional basis by 273 ppm. Data for Cd, As, Mo, V and Ag were not provided for the Interior Plains region, so comparisons could not be made.

Trace Element Content and Soil Texture

Mean concentration of trace elements within the broad textural groups (Table 4, pg 50) increases with increasing clay content following similar trends noted within individual textural classes (Table 3, pg 48). The concentration of Ag is an exception to this trend in that the Ag content is similar in all textural classes. However, as a large proportion of the soil samples had silver concentrations at or below the detection limit, this trend in the data may not accurately reflect the situation in the field. The relationship observed between soil texture and content of trace elements can be used to provide a general estimate of background levels of trace elements when on-site analytical data are not available.

Geographic Distribution of Trace Elements

Glacial erosion and weathering of bedrock and transportation and deposition of the weathered material affects the distribution and characteristics of soil parent materials. Local site conditions such as leaching and hydrogeological processes affect weathering of minerals and soil chemical characteristics such as pH and $CaCO_3$ content. These characteristics, along with physical factors such as soil drainage, in turn influence the solubility of trace elements and their bioavailability. It is this availability of individual trace elements that will determine if plants or animals will receive sufficient amounts of the element to meet their nutritional requirements, or whether they will take up the elements in toxic or surplus amounts. A brief summary of the effect of soil properties and environmental factors on the availability of each trace element is provided in the appendix, Table 7 (pg 66). The function and nutritional value of each element, together with symptoms and threshold limits for deficiency and toxicity are presented in the appendix, Table 8 (pg 69).

The following section describes the data for each trace element and illustrates in map form its general concentration and distribution in southern Manitoba. Polygon numbers appearing in the tables in the appendix and in the descriptions of the individual elements are the same as those used on the Soil Landscapes of Canada Map (Canada Soil Inventory, 1989). The classes shown on the maps /simply subdivide the range of data and do not depict any threshold or toxicity levels. This presentation is generic and reflects the observed values as background levels in the agricultural soils of southern Manitoba.

Arsenic -As

Arsenic is uniformly present in all rocks (0.5-2.5 ppm) with the exception of organic-rich shales, of which it constitutes a larger fraction (5-13 ppm), and is present at levels of <1-95 ppm in soils worldwide (Kabata-Pendias and Pendias, 1992). The background level in topsoils is typically low, but generally higher than that of the parent material (Norrish, 1975) and occasionally exceeds the threshold of contamination of 15 ppm arsenic as given by the NRCC (1978b).

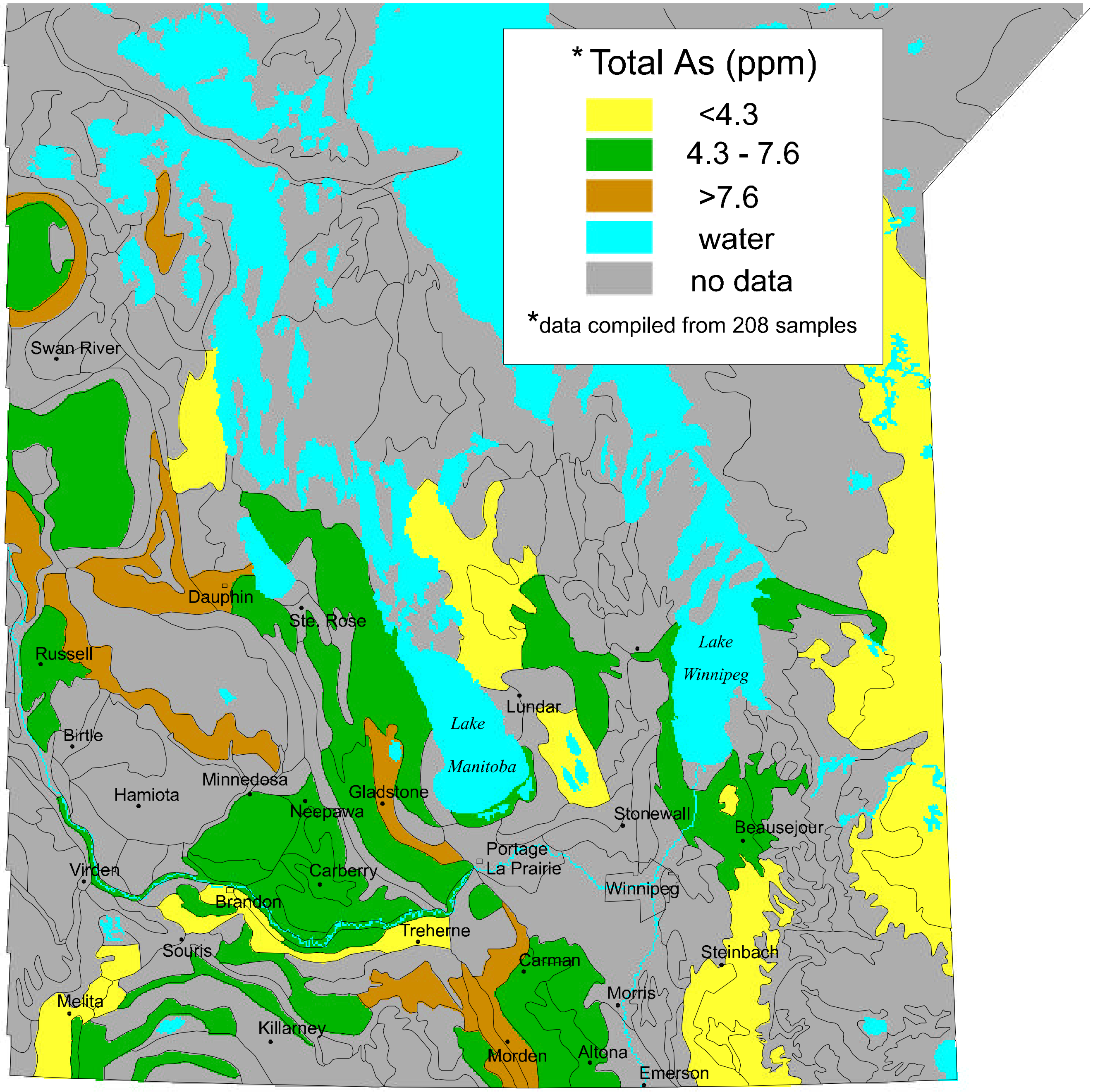
Arsenic minerals and compounds are soluble, but there is limited movement of As in soil because it is adsorbed by hydroxides, clays and organic matter (Kabata-Pendias and Pendias, 1992), and retained by iron oxides (Norrish, 1975). Therefore, As mobility is highest in sandy soils and lowest in fine textured soils and those high in iron (NRCC, 1978b). Arsenic is also subject to methylation under any redox conditions, which results in its atmospheric release (Kabata-Pendias and Pendias, 1992). Solubility of arsenic is also affected by pH and can result in leaching in acid, sandy soils (NRCC, 1978b). Unlike most trace elements, the inorganic forms of arsenic are more mobile and more toxic than the organic forms (NRCC, 1978b; Kabata-Pendias and Pendias, 1992).

Arsenic is a component of most plants but its biological function, if any, has not been determined (Kabata-Pendias and Pendias, 1992). It is not a requirement for animals or humans. It can be toxic to plants in leaf concentrations of 5-20 ppm (dry weight basis) with symptoms including necrosis, wilting, reduced growth and root discolouration (Kabata-Pendias and Pendias, 1992). Arsenic can be absorbed through roots or foliage and toxicity can occur wherever the exchange capacity of the soil has been exceeded, regardless of actual soil As levels (NRCC, 1978b). It is unlikely that phytotoxic As levels will result in the poisoning of consumers because plants will cease to grow if roots have absorbed too much As, and fruits and seeds will not have elevated levels (NRCC, 1978b). Toxicosis in animals may be a result of soil consumption, and will result in accumulation of arsenic in the organs of the animal, posing a possible health risk for humans if the organs are consumed (NRCC, 1978b). The maximum allowable concentration of arsenic in drinking water is 0.025 ppm (CCREM, 1995).

Arsenic concentrations in Manitoba soils (Table 2, pg 47) range from 0.3 to 28.5 ppm (which is within the world-wide range for soils) and 95% of the samples fall below the reported threshold of contamination for Canadian soils. The arsenic content is related to soil texture as well as the amount and characteristics of shale materials included in the soil parent material. Mean arsenic content increases from values of 4 ppm in coarse textured materials to about 12 ppm in fine textured soils, but As content is as high as 27 ppm for loamy coarse sands (Tables 3 and 4, pg 48 and pg 50). The geographic distribution shown for arsenic is incomplete due to insufficient samples. Soils with greater than average arsenic content tend to occur along the Manitoba Escarpment and in the western part of the province, particularly in landscapes in which shale bedrock has contributed to the parent material, or occurs close to the surface. Soils along the Pembina Escarpment (polygons 64 and 72, just west and southwest of Morden) have average arsenic contents in excess of 11 ppm. High contents of arsenic are also noted at other locations in western Manitoba where the soils contain significant inclusions of shale fragments or where weathered shale has contributed to the clay content of the soil (polygons 125 and 126 in the Dauphin area). (See Table 5, pg 51 for soil polygon information).

Total Arsenic (As) in Manitoba Soils

Scale 1:3 000 000



Cadmium - Cd

Cadmium is present mainly in organic-rich shales (0.22-0.30 ppm), and in igneous rocks it is highest in mafic units (0.13-0.22 ppm) (Kabata-Pendias and Pendias, 1992). It is found in soils at levels ranging from 0.06-1.1 ppm and the worldwide average is 0.53 ppm, which is also considered to be the threshold of contamination (Kabata-Pendias and Pendias, 1992).

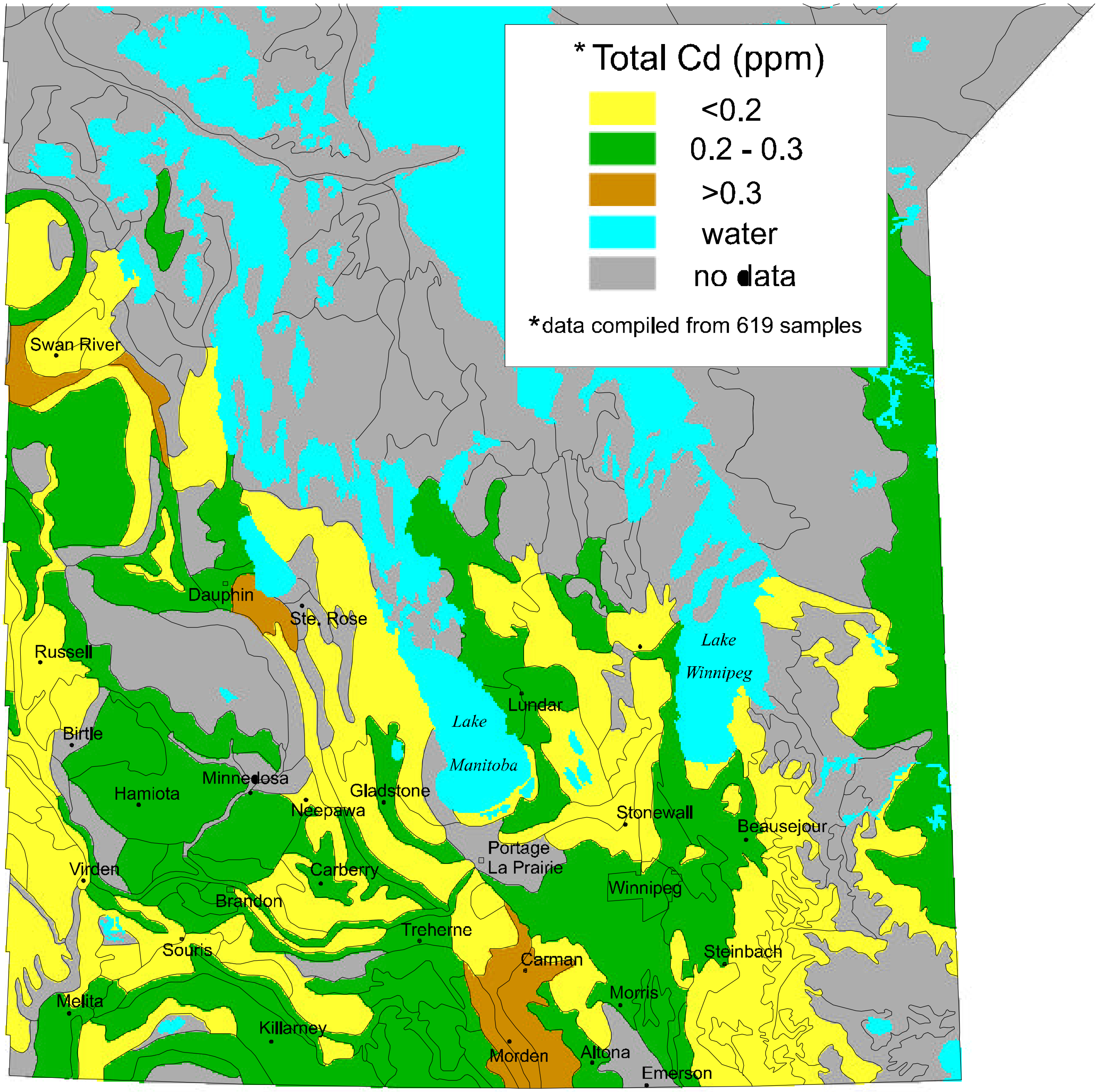
Cadmium can be found primarily in sulphide minerals such as sphalerite and pyrite (Garrett, 1998). Upon weathering, these minerals will release Cd^{2+} into solution. It is in this form that Cd is taken up by plants, although content in solution will be low, as Cd^{2+} will form complex ions and organic chelates in soil (Kabata-Pendias and Pendias, 1992). Its mobility will then be controlled primarily by pH and redox potential (Kabata-Pendias and Pendias, 1992). In acid soils Cd mobility is controlled by organic matter while in alkaline soils it is controlled by precipitation of Cd compounds ($CdCO_3$ and $Cd_3(PO_4)_2$) (Kabata-Pendias and Pendias, 1992), although this may occur only at high Cd concentrations. Immobility of Cd in alkaline soils is slightly reduced at very alkaline pH's by the formation of $CdOH^+$, which is not readily adsorbed (Kabata-Pendias and Pendias, 1992). Cd is most mobile at pH 4.5-5.5 (Kabata-Pendias and Pendias, 1992).

With no known biological functions, the main concern regarding cadmium is its role as a toxicant. It can rapidly accumulate in livestock and other animals, particularly in kidneys and other organs, creating a potential hazard for human consumption (CCREM, 1995). Cadmium is phytotoxic at leaf levels of 5-30 ppm (Kabata-Pendias and Pendias, 1992) but it can accumulate within edible portions of the plant to sub-toxic levels without resulting in any plant distress (Alloway, 1990). Cd can be taken up by plants through leaves or roots but soluble soil Cd is readily available (Kabata-Pendias and Pendias, 1992) and it is thought that this is the main source of plant Cd (FAO Soils Bulletin 65, 1992). Actual phytotoxicity can occur on polluted soils, but it is rare (Alloway, 1990), and Cd is generally not harmful to plants (FAO Soils Bulletin 65, 1992). Accumulation of cadmium in animals can cause disease if it replaces Zn in enzymes; symptoms of toxicity include renal degradation, emphysema, intestinal dysfunctions and anaemia (Lagerwerff, 1972). Cd is known to be more toxic to an animal if dietary calcium is low (CCREM, 1995). The level of Cd allowable in water for human consumption is 0 .005 ppm (CCREM, 1995).

The cadmium content of Manitoba soils (Table 2, pg 47) ranges from 0.1 to 7.9 ppm, although 95% of samples fall below the average observed in soils world-wide (0.53 ppm). The cadmium content in soil is evidently related to texture. There was approximately a four-fold increase in concentration between the coarse-textured soil group containing 0.1 ppm Cd and the fine-textured soils containing an average of 0.4 ppm (Table 4, pg 50). The highest concentrations occur in landscapes in which the soils are derived directly from shale bedrock or in which a large content of weathered shale particles comprise the soil parent material. The average concentration of cadmium is greatest along the Pembina Escarpment in southern Manitoba (polygon 64, 1.8 ppm; Polygon 72, 2.2 ppm and Polygon 73, 0.6 ppm). In western Manitoba, the Upper Swan River Plain (polygon 186) has an average Cd content of 0.5 ppm. (See Table 5, pg 51 for polygon information).

Total Cadmium (Cd) in Manitoba Soils

Scale 1:3 000 000



Chromium - Cr

There are extremely high amounts of chromium in ultramafic rocks (1600-3400 ppm), and lower amounts in felsic (4-25 ppm) and sedimentary rocks (5-120 ppm) (Kabata-Pendias and Pendias, 1992). Amounts of Cr in soil range from 1.4-1100 ppm, depending on the soil type, with an average world-wide level of 54 ppm Cr for surface soils (Kabata-Pendias and Pendias, 1992). Chromium is present in chromite ($FeCr_2O_4$), in other spinel structured minerals (Kabata-Pendias and Pendias, 1992), and ferromagnesian minerals (Garrett, 1998) . The naturally occurring forms in soil are chromite (Cr^{3+}) and chromate (CrO_4^{2-}); Cr^{3+} is the more stable form (Kabata-Pendias and Pendias, 1992).

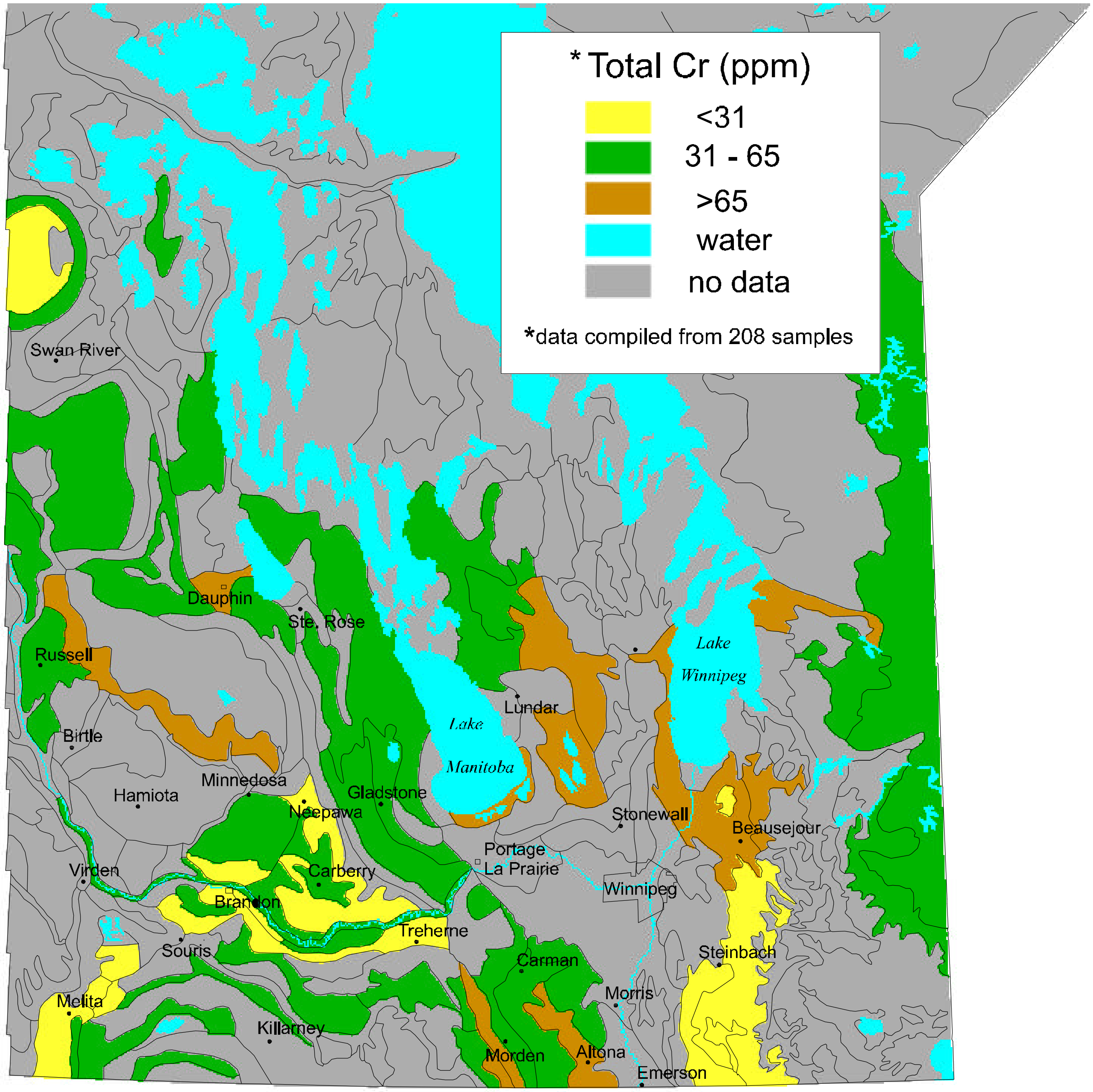
Chromite is resistant to weathering but may oxidize to chromate (Cr^{6+}), (Kabata-Pendias and Pendias, 1992). Cr^{3+} is only slightly mobile under very acid conditions, and it is almost completely precipitated at pH 5.5 (Kabata-Pendias and Pendias, 1992). While the presence of organic matter promotes reduction of Cr^{6+} to Cr^{3+}, which may lead to low plant availability (Kabata-Pendias and Pendias, 1992), the presence of Mn oxides encourages oxidation of Cr^{3+} to Cr^{6+}, which is very toxic and more readily available (McBride, 1994). Sandy soils and organic soils are low in Cr (Kabata-Pendias and Pendias, 1992) but Cr^{3+} may be more available in sandy soils due to the lower cation exchange capacity (NRCC, 1976).

There is no evidence that chromium is essential for plants but there are some reports of growth stimulation by Cr^{3+} (Kabata-Pendias and Pendias, 1992; McGrath and Smith, 1990). Cr^{3+} is required for removal of excess glucose in mammals (Scott, 1972) and deficiencies have been found to occur in humans and animals (NRCC, 1976). Cr^{6+} is toxic to both plants and animals (Kabata-Pendias and Pendias, 1992). Phytotoxicity occurs at leaf levels of 5-30 ppm (dry weight basis) and there is some evidence of toxicity to livestock grazing on plants high in Cr (Kabata-Pendias and Pendias, 1992), but most Cr taken up by plants remains in the roots (McGrath and Smith, 1990). Maximum allowable levels for water used for human consumption have been set at 0.05 ppm (CCREM, 1995).

The chromium content of Manitoba soils (median value of 46 ppm, Table 2, pg 47), is well below the world-wide average of 54 ppm. The highest values occur in the clay textured soils of the fine textural group (83 ppm) and the lowest concentrations are in the coarse textured group (25 ppm) (Table 4, pg 50). The distribution pattern shown in the map of southern Manitoba is not complete due to insufficient samples. However, the lithology of the soil parent material, particularly the shale content, does affect the chromium content of the soil. The highest concentrations of chromium observed in Manitoba occurred in landscapes in which the parent material contained inclusions of shale bedrock. This occurs along the lower Pembina Escarpment in southern Manitoba where Cr contents ranged from 81 ppm (polygon 72) to 104 ppm (polygon 64) and in west-central Manitoba where samples from the Porcupine Escarpment contained 64 ppm. Several landscapes in northern portions of the Red River Plain dominated by heavy clay soils contained average Cr concentrations ranging from 75 to 85 ppm. Soils immediately south of Riding Mountain (polygon 116) had 70 ppm of chromium and several samples from the southern Interlake region (polygons 140 and 160) had Cr contents ranging from 78 to 110 ppm (Table 5, pg 51).

Total Chromium (Cr) in Manitoba Soils

Scale 1:3 000 000



Cobalt - Co

The largest amounts of cobalt are present in ultramafic (100-200 ppm) and mafic rocks (35-50 ppm) with a substantial amount present in organic-rich shales (14-20 ppm) (Kabata-Pendias and Pendias, 1992). The overall range for cobalt in soils on a world-wide basis is 0.1-70 ppm (Kabata-Pendias and Pendias, 1992) and the average amount is 8 ppm (Tisdale et al., 1985). It is present in soil as Co^{2+} and Co^{3+} and possibly as $Co(OH)^{3-}$ (Kabata-Pendias and Pendias, 1992). The main form in solution is Co^{2+}(McBride, 1994), although the total amount of cobalt in solution will be low.

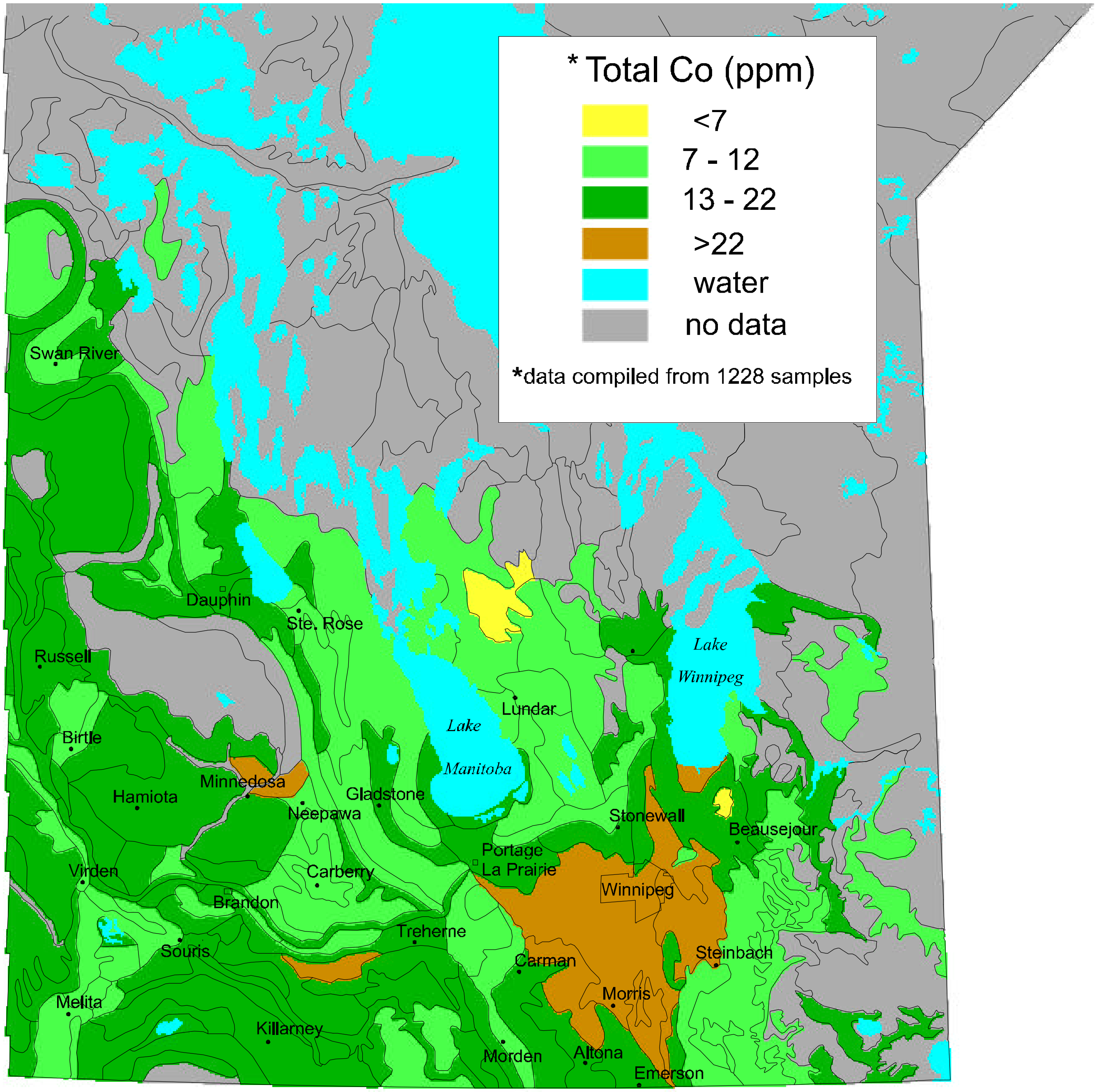
The status of available Co in soil can be estimated based on geological and soil information (Kabata-Pendias and Pendias, 1992). Manganese oxide minerals are the most important factor governing Co distribution and availability in the soil (Kabata-Pendias and Pendias, 1992; McKenzie, 1975). Crystalline Mn oxide minerals can retain almost all soil Co, even that applied to soil as fertilizer (Tisdale et al., 1985), and cobalt held in such a way is unavailable to plants. Iron oxides, clay minerals and organic matter may also adsorb cobalt, and the availability is affected by the type of clay minerals and organic matter on which it is adsorbed (Kabata-Pendias and Pendias, 1992). Montmorillonite and illite will strongly retain Co, and organic chelate bound Co is very mobile (Kabata-Pendias and Pendias, 1992). Cobalt is mobile in oxidizing, acid environments; and soils with low Co levels tend to be either I) alkaline and calcareous, ii) high in organic matter content, iii) acidic and highly leached, or iv) high in Fe and Mn (Kabata-Pendias and Pendias, 1992).

Cobalt is essential for blue-green algae and N_2-fixing rhizobia but its essentiality for higher plants is not proven although it has been shown to be beneficial to plant growth (Kabata-Pendias and Pendias, 1992). In ruminants, it is the precursor to vitamin B_{12}, for which the sole natural source is plant Co (Kabata-Pendias and Pendias, 1992; Tisdale et al., 1985). Deficiencies lead to inhibition of N_2 fixation in legumes, but this does not generally occur as the requirements of the rhizobia are low (Kabata-Pendias and Pendias, 1992). It is widely accepted that soil Co levels below 5 ppm (originally from Kubota, 1964) will lead to deficiency problems in ruminants which include emaciation, muscular atrophy and anaemia (Tisdale et al., 1985). Under natural conditions, toxicity to either plants or animals is unlikely, but cobalt toxicity can be a problem in areas with high natural Co levels and particularly in areas that are Co contaminated (Kabata-Pendias and Pendias, 1992). There is no guideline for the maximum allowable level of cobalt in drinking water at this time (CCREM, 1995).

The cobalt content of Manitoba soils (Table 2, pg 47) ranges from 2 to 37 ppm and the median value of 12 ppm exceeds the world-wide average of 8 ppm. The lowest amounts of cobalt occurred in the coarse textured materials (8 ppm) and gradually increased with increasing clay content to values of 19 ppm in the fine textured soils (Table 3 and 4, pg 48 and 50). The geographic distribution of cobalt in southern Manitoba soils is not strongly influenced by the lithologic origin or nature of the soil parent material but appears to be more strongly related to the texture of the soil materials. The lowest concentrations occurred in the rapidly drained sands and the highest concentrations occurred in the heavy clay soils of the Red River Plain (polygons 69, 71, 89 and 90) and the Dauphin Lake Plain (polygon 125) (Table 5, pg 51).

Total Cobalt (Co) in Manitoba Soils

Scale 1:3 000 000



Copper - Cu

Copper is found in relatively high levels in mafic rocks (60-120 ppm) and argillaceous sediments (40-60 ppm), and in much lower levels in limestones (2-10 ppm) (Kabata-Pendias and Pendias, 1992). Values for soil contents vary but generally range from 1-40 ppm with an average of 9 ppm in the United States (Tisdale et al., 1985). Mean copper contents for uncontaminated soils world wide range from 13-24 ppm, but the overall range for world soils is higher (1-140 ppm) depending on the nature of the soil parent materials (Kabata-Pendias and Pendias, 1992).

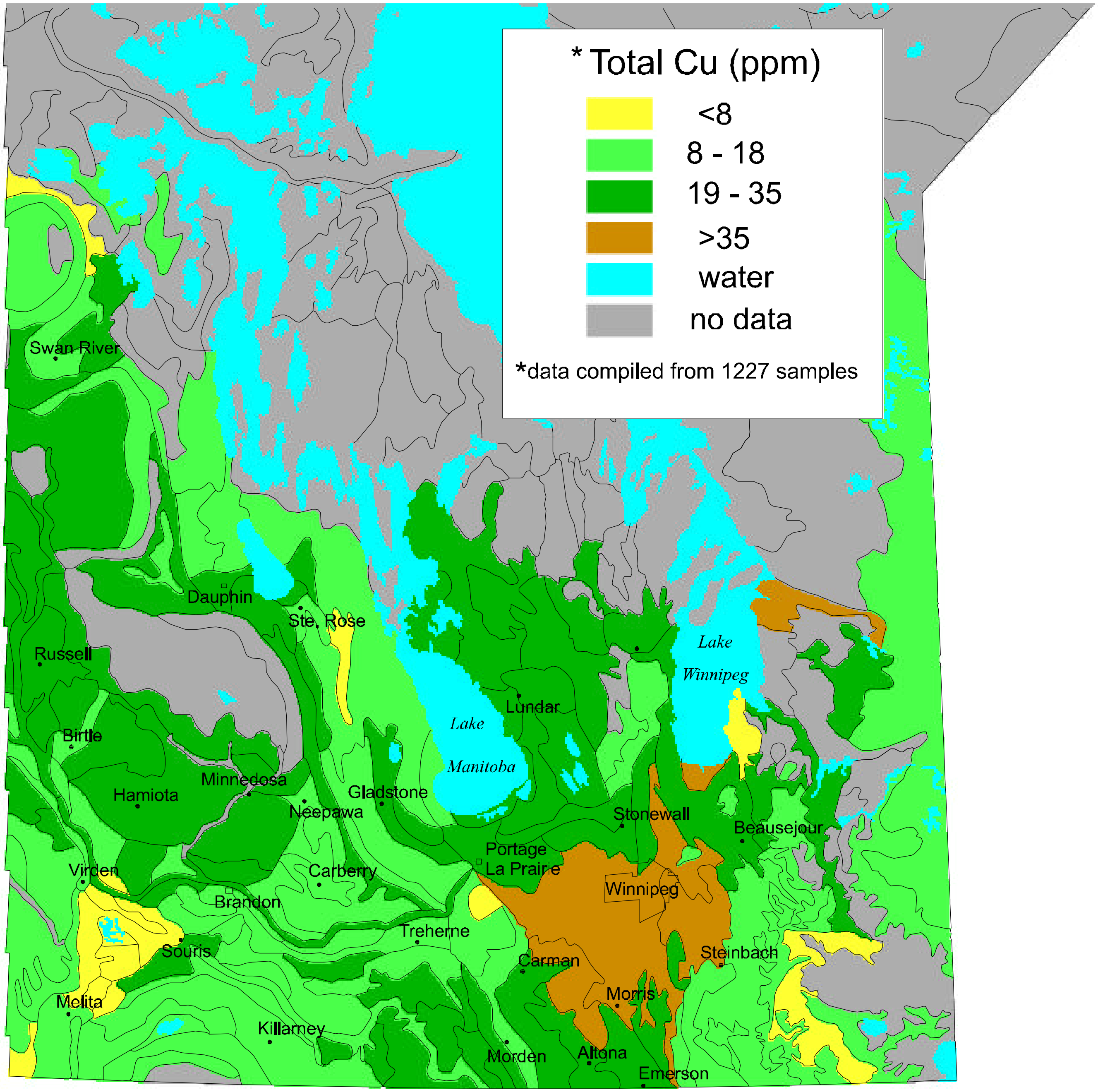
Copper in soil can be fixed by adsorption, precipitation, organic chelation and complexation, as well as microbial fixation, and is basically immobile in soils (Kabata-Pendias and Pendias, 1992). It can precipitate with sulfides, carbonates and hydroxides and is tightly held on organic and inorganic exchange sites, with the bulk of copper adsorption occurring on Fe and Mn oxides (Kabata-Pendias and Pendias, 1992), which is a non-exchangeable form (Tisdale et al., 1985). The main form of copper in solution is that of soluble organic chelates, but solubility of all forms of Cu decreases at pH 7-8 (Kabata-Pendias and Pendias, 1992). Acid leached sandy soils and calcareous sandy soils may be low in soluble copper (Tisdale et al., 1985) and mobility of copper is low in reduced and neutral soils (McBride, 1994). Cu mobility may be higher under high pH because of Cu^{2+} complex formation which may increase overall Cu solubility (McBride, 1994).

Copper functions in oxidation, photosynthesis, and metabolism; consequently, it is essential in plants (Kabata-Pendias and Pendias, 1992). As well, it is necessary in animal nutrition where it plays a role in oxidase functions (Kubota and Alloway, 1972). In particular, ruminant health requires that a dietary balance of a two parts Cu to one part Mo (Cu:Mo ratio of 2:1) be maintained (CCREM, 1995). Deficiencies can occur in plants at dry weight levels of 2-5 ppm (Kabata-Pendias and Pendias, 1992). Levels toxic to plants are 20-100 ppm (dry weight basis) (Kabata-Pendias and Pendias, 1992) but 15 ppm in feed is generally toxic to animals (CCREM, 1995). Copper accumulates in the organs of animals which can lead to problems for human consumption (CCREM, 1995). The maximum concentration of copper allowable in drinking water is 1.0 ppm, which is based on aesthetic concerns as it is generally non-toxic to humans (CCREM, 1995).

The copper content of Manitoba soils (Table 2, pg 47), ranges from 1 to 68 ppm from which falls within the range established for copper in soils on a world-wide basis. The median content of 18 ppm is double the American average of 9 ppm, but within the world-wide range of means. The low average values of copper (7 ppm) observed in the coarse-textured soils group gradually increase with increasing clay content to an average value of 33 ppm in the fine textured soils group (Table 4, pg 50). Copper deficiency has been noted on well drained, sandy, leached soils having concentrations of less than 5 ppm (Table 5, pg 51, polygons 15, 24, 34, and 137). The geographic distribution of copper is fairly uniform in Manitoba soils, variability being most closely related to soil texture rather than the lithology of the parent material. Highest average concentrations of copper occur in the heavy clay soils of the Red River Plain (polygons 69, 89 and 90) and the Dauphin Lake Plain (polygon 125 containing 35 ppm) (Table 5, pg 51).

Total Copper (Cu) in Manitoba Soils

Scale 1:3 000 000



Iron - Fe

Iron is present mainly in ultramafic rocks at levels of 9.4-10.0%, and is lowest in limestones (0.4-1.0%) and sandstones (1.0-3.0%) (Kabata-Pendias and Pendias, 1992). It is commonly found in soil in amounts ranging from 0.5-5.0% (Kabata-Pendias and Pendias, 1992) with an overall average soil content of 3.8% (Tisdale et al., 1985). The most common minerals containing iron are hematite and goethite (Kabata-Pendias and Pendias, 1992; Norrish, 1975). In soil, iron occurs predominantly as oxides and hydroxides, it is present in soil solution in 3+ and 2+ oxidation states and as iron chelates, and is absorbed by plants mainly in the form of Fe^{2+} (Kabata-Pendias and Pendias, 1992).

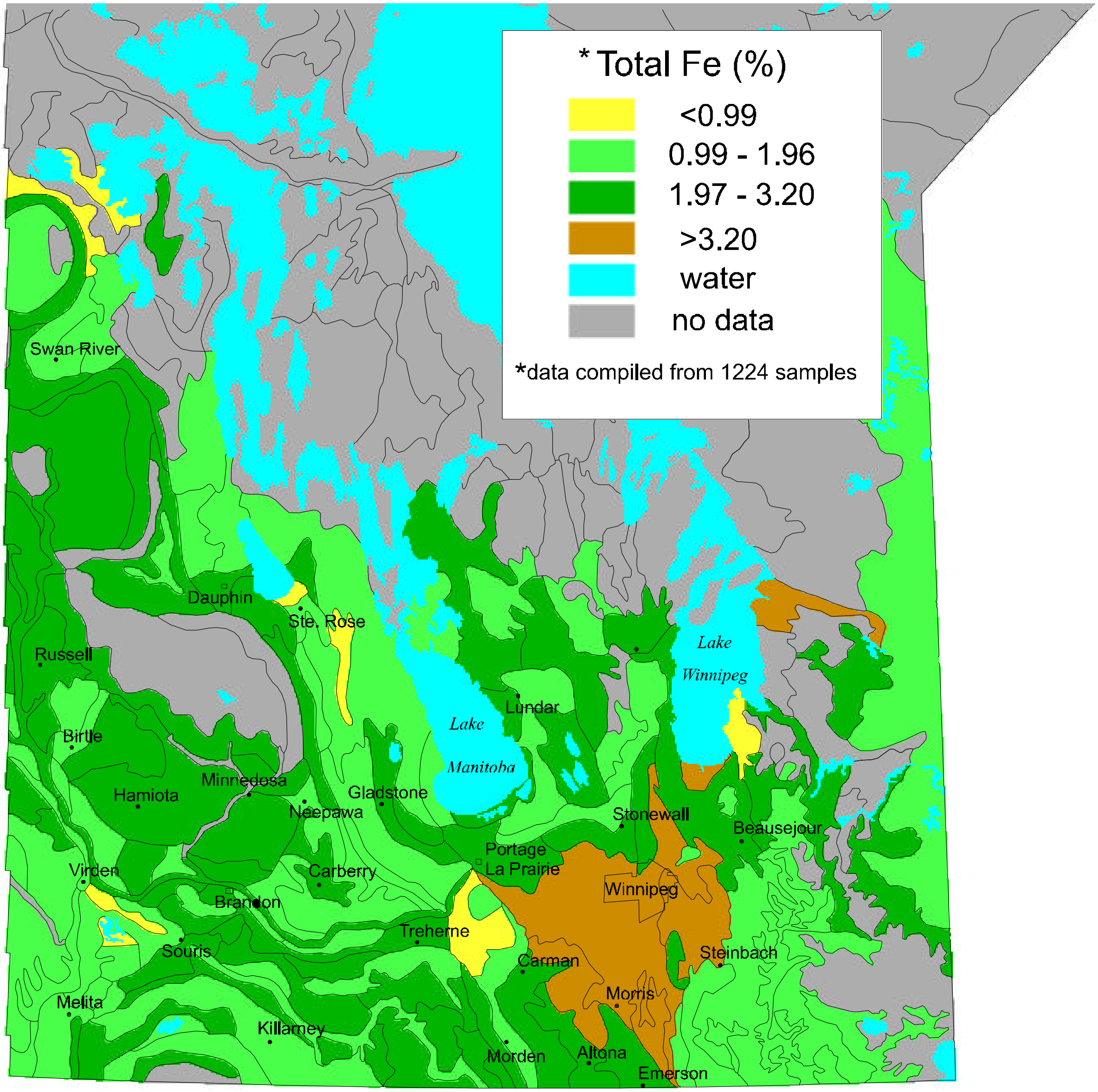
The solubility of Fe is affected mainly by hydrolysis and complexation (Kabata-Pendias and Pendias, 1992). Soil aeration and pH also affect the mobility of Fe. Increasing pH and oxidized conditions lead to Fe precipitation whereas acid reducing conditions result in higher solution concentration of Fe (Kabata-Pendias and Pendias, 1992). Under anaerobic conditions, Fe^{3+} is reduced to Fe^{2+} (Kabata-Pendias and Pendias, 1992) , which is also the dominant form of Fe at pH<6.5 (Tisdale et al., 1985). Iron has a high affinity for soluble organic chelates, and this may result in higher solution Fe levels than otherwise possible at normal pH*s (Tisdale et al., 1985). Deficiencies are generally caused by unavailability of soil iron rather than a low iron content in soil, and are likely to occur on soils which are well aerated, calcareous, alkaline or high in Mn (Kabata-Pendias and Pendias, 1992).

Iron is essential to all organisms. It is a cofactor in enzymes and heme proteins and is involved in photosynthesis and N_2 fixation (Kabata-Pendias and Pendias, 1992). Plants vary widely among species and genotypes in their susceptibility to deficiency and toxicity so that threshold values are difficult to estimate (Kabata-Pendias and Pendias, 1992). Incidences of Fe toxicity to plants have not been reported under natural conditions (Jones, 1972). Animals require iron at levels of 50-100 ppm in feed on a dry weight basis (Kabata-Pendias and Pendias, 1992) and suffer toxicosis at levels approaching 3000 ppm (NAS/NAE, 1973). The maximum allowable iron content in water for human consumption was set at 0.3 ppm based on aesthetic, rather than health concerns (CCREM, 1995).

The iron content of Manitoba soils ranges from 0.17 to 5 % (Table 2, pg 47), falling within the range established for soils on a world-wide basis. The median iron content is 1.96 % (Table 2, pg 47). As with other elements such as cobalt, copper and lead, the mean iron content is lowest in the coarse-textured soil group (1.11 %) and increases with increasing clay content to 3.14 % in the fine textured soils (Table 4, pg 50). The geographic distribution of iron is relatively uniform in soils of southern Manitoba (Table 5, pg 51) and does not appear to be strongly influenced by the lithology of the soil parent material but rather is more closely related to soil texture. It is interesting to note that there is a close correlation between Fe content and Co, Cu, Ni, V and Zn contents in polygons 69, 71, 86, and also in the dominantly clay textured soils located around the Winnipeg area (polygons 89, 90, 91) and in the Dauphin area (polygon 125) (Table 5, pg 51). This may be a reflection of the extent to which these elements are sequestered by Fe oxides in the soil.

Total Iron (Fe) in Manitoba Soils

Scale 1:3 000 000



*data compiled from 1224 samples

Lead - Pb

Lead occurs as a sulfide in rocks and replaces K, Ba, Sr and Ca in minerals (Norrish, 1975). The largest presence of lead occurs in argillaceous sediments (20-40 ppm) and shales (18-25 ppm), but amounts are also high in felsic rocks (15-24 ppm) (Kabata-Pendias and Pendias, 1992). The overall range of lead in world soils is 3-189 ppm with a range in means of 10-67 ppm and an overall average level of 32 ppm (Kabata-Pendias and Pendias, 1992). A threshold of contamination of 20 ppm has been suggested based on the low lead levels found in Alaskan soils (range of means: 22-28 ppm) (Kabata-Pendias and Pendias, 1992). The range in amounts of lead in remote areas tends to be from 10-30 ppm, but levels in other soils are higher, 30-100 ppm (Davies, 1990).

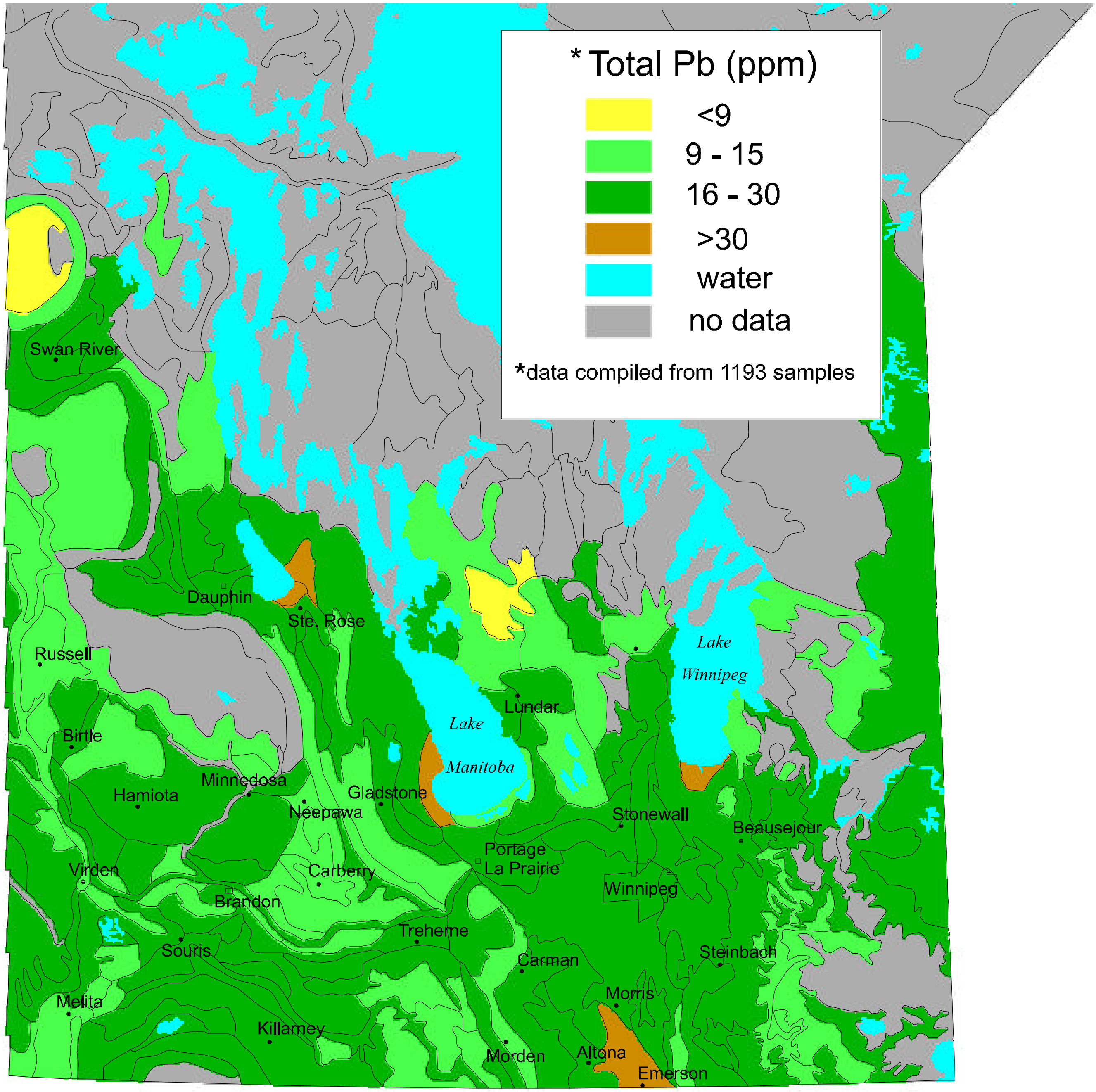
Least mobile of the heavy metals, (Kabata-Pendias and Pendias, 1992), lead accumulates in the surface horizons of soils and is not usually leached (Davies, 1990). Its concentration in solution is low, and this limited amount is available for plant uptake (Davies, 1990). It exists in soil solution mainly as Pb^{2+}, but it may also occur in the Pb^{4+} oxidation state (Kabata-Pendias and Pendias, 1992). In soil it is mainly associated with organic matter, clay minerals and oxides of Mn, Fe and Al (Kabata-Pendias and Pendias, 1992). Lead is most available under acid conditions (particularly in sandy soil) (NRCC, 1978a) and precipitates as hydroxides, phosphates and carbonates as pH increases (Lagerwerff, 1972). In association with Mn oxides, the solubility of lead decreases as Pb^{2+} is oxidized to Pb^{4+} (McBride, 1994). There is limited availability of lead in all soils unless the cation exchange capacity is saturated and lead is present in soluble organic complexes (NRCC, 1978a).

Lead is a non essential element for plants, animals and humans. It is toxic to plants at leaf levels of 30-300 ppm (dry weight basis), at which point plants exhibit dark green leaves, wilting, and stunted foliage and roots (Kabata-Pendias and Pendias, 1992). Although lead can be absorbed through roots and foliage (Lagerwerff, 1972) phytotoxicities are rarely observed under field conditions. Lead is highly toxic to animals at a level of 30 ppm Pb in diet on a dry weight basis (FAO Soils Bulletin 65, 1992) and leads to efficiency problems in red blood cell synthesis (NRCC, 1978a). Translocation of lead within plants is low (McBride, 1994; Kabata-Pendias and Pendias, 1992), so the main health concern for humans and animals is ingestion of soil with plants (McBride, 1994), although elevated Pb levels in root crops may be a problem. The guideline established for lead in water for human consumption is 0.01 ppm (CCREM, 1995).

The concentration of lead observed in Manitoba soils varies from 3 to 55 ppm with a median content of 15 ppm (Table 2, pg 47). This range falls within the range of means established for soils world-wide. The average lead content is lowest in coarse-textured soils (13 ppm), increasing gradually with increasing clay content to 21 ppm in fine-textured materials (Table 4, pg 50). There does not appear to be a strong relationship between lead content in soils and the origin or lithology of the parent material. The highest mean values of lead in Manitoba soils were observed in samples from three landscapes dominated by poorly drained soils (polygons 92, 86 and 123), and one imperfectly drained soil (polygon 54) (Table 5, 51).

Total Lead (Pb) in Manitoba Soils

Scale 1:3 000 000



Manganese - Mn

Mafic rocks contain the largest amounts of manganese (1200-2000 ppm) while sandstones contain relatively small amounts (100-500 ppm) (Kabata-Pendias and Pendias, 1992). There is a wide range of Mn in world soils (7-9200 ppm) with a calculated grand mean of 437 ppm (Kabata-Pendias and Pendias, 1992). Manganese occurs in soils and minerals mainly in the forms of Mn^{2+}, Mn^{3+}, and Mn^{4+} (McBride, 1994; Kabata-Pendias and Pendias, 1992) but only Mn^{2+} is absorbed by plants (Tisdale et al., 1985).

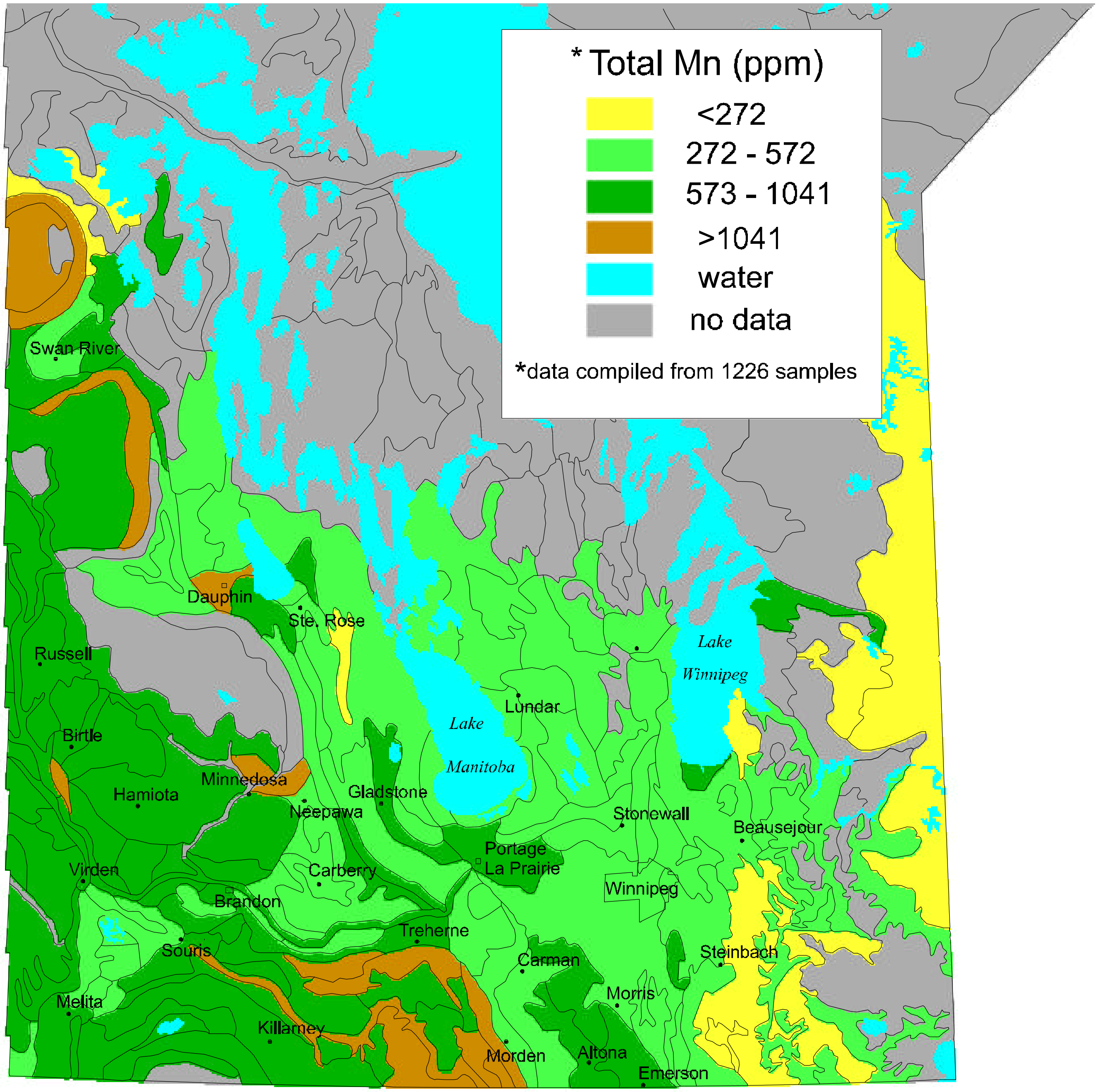
Mn forms a high amount of hydroxides and oxides and may form simple or complex ions in solution (Kabata-Pendias and Pendias, 1992). It tends to accumulate in surface horizons due to adsorption by organic matter and clay (Kabata-Pendias and Pendias, 1992). Manganese rapidly switches between oxidized and reduced states under all soil conditions so that redox potential, along with pH, governs Mn solubility in soil (Kabata-Pendias and Pendias, 1992). Solubility increases under reducing conditions in which manganese is present as Mn^{2+}, and decreases under oxidizing conditions (Kabata-Pendias and Pendias, 1992). As pH decreases, solution Mn concentration increases, to the point that it may be present in toxic levels at acid pH*s, while most basic and neutral soils are potentially deficient (Tisdale et al., 1985). Toxicity problems are likely to be found on well drained soils with a pH<5.5, poorly drained soils with a pH of 6 or greater, or soils with a pH greater than 8 (Kabata-Pendias and Pendias, 1992).

Manganese is essential for the production of oxygen in plant chloroplasts, and it affects plant nutrition indirectly through its involvement in nitrate reduction (Kabata-Pendias and Pendias, 1992). Deficiency symptoms of necrosis and reduced turgor are exhibited at plant leaf levels of 10-30 ppm Mn (dry weight basis) and toxicity is not evident until leaf concentrations of 400-1000 ppm are attained (Kabata-Pendias and Pendias, 1992). Manganese is also a requirement for ruminants at the level of 40 ppm in forages (Boila et al., 1985). Deficiencies in animals are uncommon but most often involve poultry, which have a higher Mn requirement (Kubota and Alloway, 1972). Manganese is also essential in the human diet and the maximum allowable content of 0.05 ppm for drinking water is based mainly on aesthetic concerns (CCREM, 1995).

The manganese content of Manitoba soils ranges from 24 to 5200 ppm. The median concentration of 572 ppm (Table 2, pg 47) is higher than the calculated grand mean for world soils. The average manganese content is lowest in coarse-textured materials (397 ppm), increasing gradually with increasing clay content to 710 ppm in the fine-textured soils (Table 4, pg 50). The geographic distribution of Mn in Manitoba soils is influenced by lithologic characteristics and origin of the soil parent material as well as by local soil conditions such as pH, drainage and oxidation - reduction status. In general, soils below the Manitoba Escarpment in the Manitoba Plain exhibit average manganese contents of less than about 572 ppm whereas soils above the Escarpment in the Saskatchewan Plain have manganese contents of 573 and greater. Highest values occur in upland portions of the Saskatchewan Plain such as the Pembina Hills, Duck Mountain (polygon 129) and the Porcupine Hills (polygons 13 and 14) where concentrations in excess of 1041 ppm are noted (Table 5, pg 51). Highly calcareous glacial till soils in the Manitoba Plain consisting dominantly of limestone materials generally have Mn contents of about one-half of the concentrations observed in soils developed on shaly materials.

Total Manganese (Mn) in Manitoba Soils

Scale 1:3 000 000



Mercury - Hg

Mercury is present mainly in sedimentary rocks, especially shales (180-400 ppb) and argillaceous sediments (200-400 ppb) (Kabata-Pendias and Pendias, 1992). The overall range of mercury in soils is 8-1110 ppb, with a world-wide range of means of 50-260 ppb Hg (Kabata-Pendias and Pendias, 1992), but agricultural plains soils generally contain 70 ppb Hg (NRCC, 1979). Organic soils occupy the high end of the world-wide range. Kabata-Pendias and Pendias (1992) found background levels difficult to estimate and proposed 300 ppb Hg to be a threshold level of Hg contamination in soil. Mercury is found in three states in nature: elemental (Hg^0), mercurous Hg(I) (Hg_2^{2+}), and mercuric Hg(II) (Hg^{2+}) and is present in the minerals cinnabar and metacinnabar (NRCC, 1979), and in trace amounts in sulphides and antimonides (Garrett, 1998).

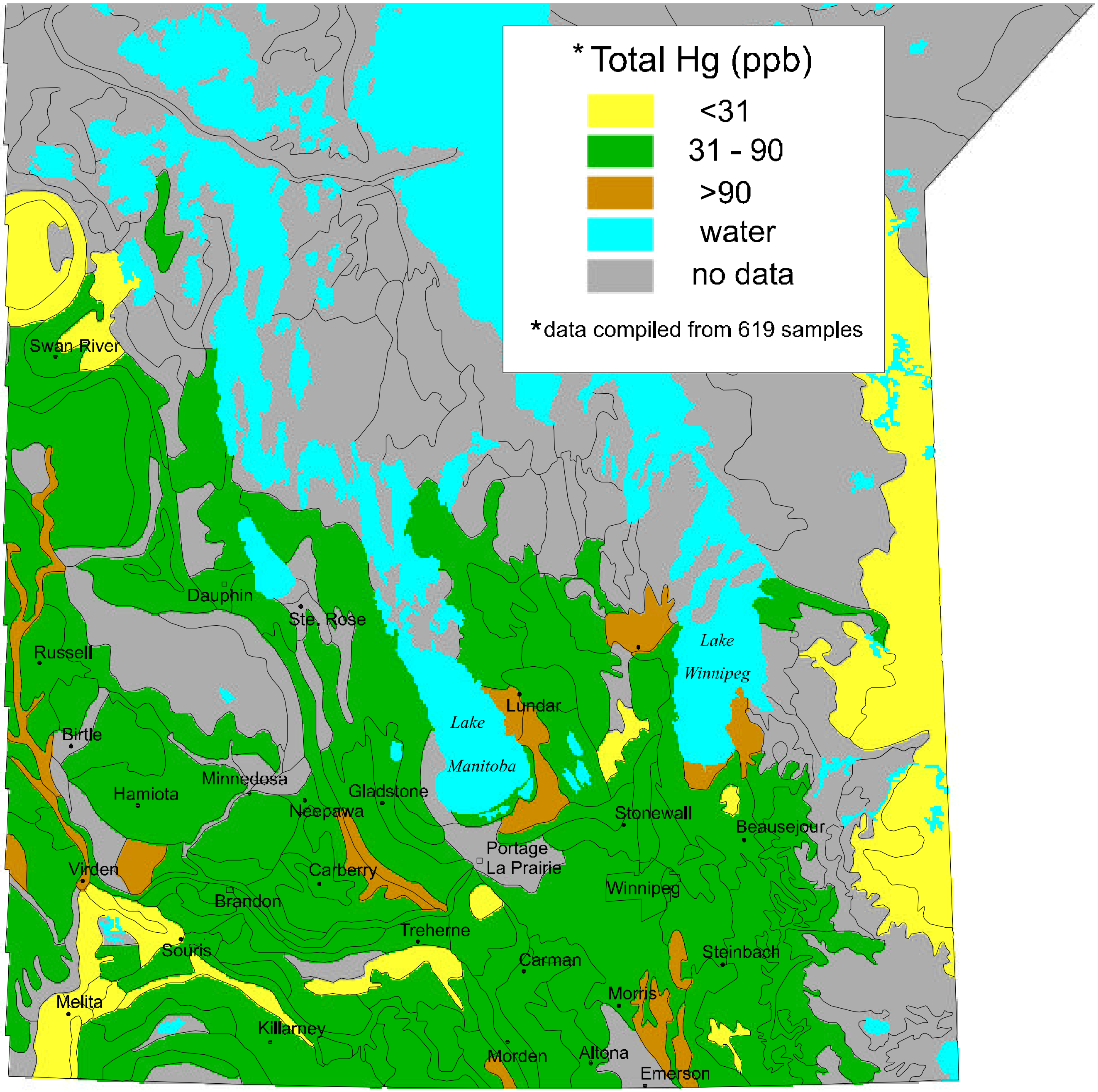
Mercury is not mobile during weathering and is retained in the soil mainly as slightly mobile organocomplexes (Kabata-Pendias and Pendias, 1992). The accumulation of Hg is controlled by complex formation and precipitation; it tends to be higher in organic soils as humus can bind Hg, and is present in surface soils in amounts several times greater than in the subsoils (Kabata-Pendias and Pendias, 1992). It is strongly adsorbed even in sandy soils, but leaching can occur under conditions favouring organic matter leaching (Kabata-Pendias and Pendias, 1992). In an acid environment, organic forms may be subject to leaching, while in alkaline and neutral environments, inorganic forms tend to leach (Kabata-Pendias and Pendias, 1992). Sorption varies with pH and is highest at pH 4-5 (Kabata-Pendias and Pendias, 1992). Mercury is persistent in aerobic soils but is partly converted to soluble monomethyl and gaseous dimethyl Hg complexes under waterlogged or flooded conditions (Lagerwerff, 1972). Methylated mercury is mobile and bioavailable and forms easily under contaminated conditions (Kabata-Pendias and Pendias, 1992).

Mercury is not essential to plants, animals or humans. It is toxic to plants at levels of 1000-3000 ppb (dry weight basis), resulting in chlorosis and severe stunting of seedlings and roots (Kabata-Pendias and Pendias, 1992). However, as availability to plants is low, phytotoxicity is generally not a problem (Steinnes, 1990). In fact, increasing levels in soils lead to only small increases in plants (NRCC, 1979), and translocation is generally limited as mercury accumulates in the roots (Steinnes, 1990), reducing problems caused by consumption of plant foliage. However, volatile forms can be absorbed foliarly by plants (Kabata-Pendias and Pendias, 1992). It is most serious in its methylated and volatilized elemental forms (Kabata-Pendias and Pendias, 1992). The organic form is far more toxic than the inorganic form and more readily absorbed, although both inorganic and organic forms are readily bioavailable (Kabata-Pendias and Pendias, 1992). In animals, Hg accumulates in the liver and kidneys, making it a hazard to both the animals and human consumers (NRCC, 1979). The maximum allowable concentration of mercury in water used for human consumption is 1 ppb (CCREM, 1995).

The mercury content of Manitoba soils ranges from 10 ppb to 210 ppb with a median content of 50 ppb (Table 2, pg 47). This concentration is similar to the range of means established for the mercury content of soil on a world-wide basis. The mercury content is lowest in coarse-textured soils (40 ppb) increasing gradually with increased clay content to 70 ppb in the fine-textured soils (Table 4, pg 50). The mercury content of southern Manitoba soils generally exceeds 50 ppb (Table 5, pg 51) with local areas of soil exceeding 90 ppb. Soil texture exhibits a stronger influence on soil mercury content than does the lithological characteristics of the parent material.

Total Mercury (Hg) in Manitoba Soils

Scale 1:3 000 000



Molybdenum - Mo

Molybdenum content is highest in organic rich sediments (2.0-2.6 ppm), shales (0.7-2.6 ppm) and felsic rocks (1-2 ppm) and lowest in limestones (0.16-0.40 ppm) (Kabata-Pendias and Pendias, 1992). It is present in soils world-wide at levels of 0.1-7.35 ppm (Kabata-Pendias and Pendias, 1992) and an average of 2 ppm (Tisdale et al., 1985). Mo is present in soils in both the 3+ and 6+ (MoO_4^{2-}) oxidation states, but it predominates as MoO_4^{2-} (McBride, 1994) and is taken up by plants in this form (Kabata-Pendias and Pendias, 1992). Too many factors influence Mo availability for total soil Mo levels to be an accurate predictor of potential deficiency or toxicity problems (Gupta and Lipsett, 1981).

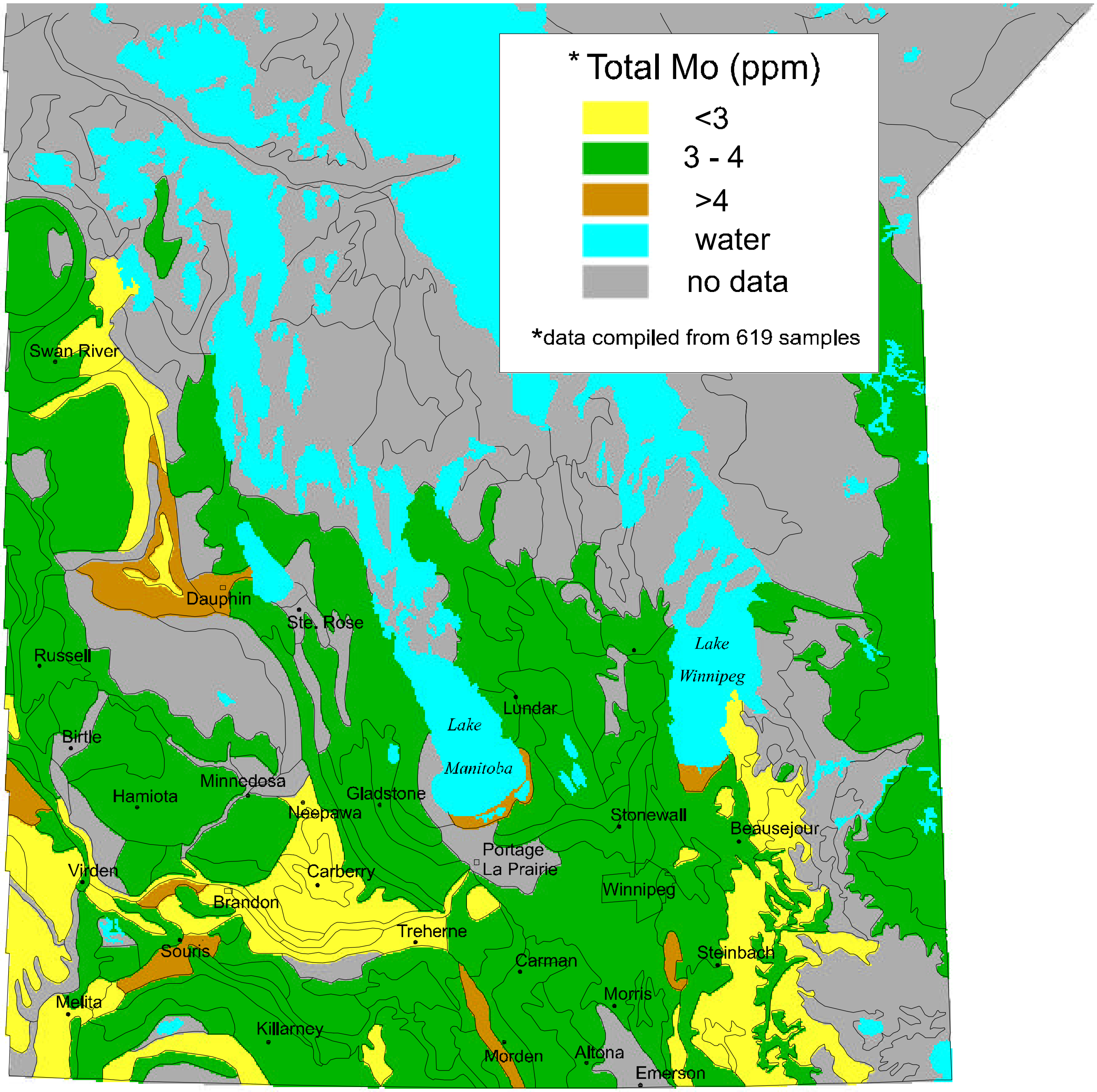
Molybdenate (MoO_4^{2-}) is easily mobile but can precipitate with organic matter, $CaCO_3$, and several cations: Pb^{2+}, Cu^{2+}, Zn^{2+}, Mn^{2+} and Ca^{2+} (Kabata-Pendias and Pendias, 1992). MoO_4^{2-} can also be adsorbed by Fe, Al and Mn hydrous oxides (Kabata-Pendias and Pendias, 1992; Tisdale et al., 1985), but is mainly associated with organic matter and Fe oxides in soil (Kabata-Pendias and Pendias, 1992). Mo solubility is governed by pH and redox conditions. It can form soluble thiomolybdenates under reducing conditions and its solubility increases with increasing pH (Kabata-Pendias and Pendias, 1992). In fact, soil pH is the single most important factor controlling Mo uptake by plants (Gupta and Lipsett, 1981). Instances of Mo deficiency are associated with soils that are strongly acid to acid, well drained, high in Fe and Al oxides or high in SO_4-S (Kabata-Pendias and Pendias, 1992) while toxic conditions are linked to poorly drained, alkaline, calcareous, clayey or peaty soils (McBride, 1994).

Essential to plant nutrition, molybdenum is involved in N_2 fixation, NO_3^- reduction and valence changes (Kabata-Pendias and Pendias, 1992). Its requirement is related to the source of N, so that plants supplied with NH_4-N need less Mo than those receiving NO_3^--N (Kabata-Pendias and Pendias, 1992). Deficiencies can occur in plants at levels of 0.1-0.3 ppm and can include such symptoms as leaf deformation due to excess NO_3^- (Kabata-Pendias and Pendias, 1992) and terminal scorch on leaves (Gupta and Lipsett, 1981). Mo is also essential in animal nutrition (McBride, 1994) and can result in Cu toxicity if present in deficient amounts (Kubota and Alloway, 1972). Phytotoxicity occurs at levels of 10-50 ppm Mo in plant tissues but this is rare under field conditions (Kabata-Pendias and Pendias, 1992). Levels above 5 ppm Mo in forage can result in Mo induced Cu deficiency in ruminants (Tisdale et al., 1985; Kubota and Alloway, 1972). The Canadian Water Quality Guidelines give no recommendation for Mo levels in water for human consumption, but guidelines for livestock water consumption include a maximum allowable Mo level of 0.5 ppm, a level which is half that of the Cu recommendation (CCREM, 1995).

The molybdenum content of Manitoba soils ranges from 1 to 31 ppm (Table 2, pg 47). The maximum level reported is high, but 95% of the samples fall within the world-wide range. This range and the median content of 3 ppm is slightly above the world-wide average of 2 ppm. The molybdenum content generally increases with clay content; the average molybdenum content in coarse-textured materials (2 ppm) is about one half of the average concentration of 4 ppm molybdenum observed in the fine-textured soils (Table 4, pg 50). The distribution of molybdenum throughout southern Manitoba is quite variable, however, areas of greatest concentration appear to occur in the Saskatchewan Plain. Soils in some of these landscapes have higher shale contents and are characterized by Mo concentrations in excess of 4 ppm. Individual soil series in the Dauphin area (Edwards, Keld, Paulson and Meharry series in Table 6, pg 57) are characterized by mercury concentrations that exceed the average Manitoba concentrations by a factor of 2.5 to 7. These large concentrations result from the higher shale contents in the soil parent materials of these areas.

Total Molybdenum (Mo) in Manitoba Soils

Scale 1:3 000 000



Nickel - Ni

Nickel is extremely high in ultramafic rocks (1400-2000 ppm) and lower in mafic rocks (130-160 ppm). Of the sedimentary rocks, it is highest in the organic rich shales (40-90 ppm) (Kabata-Pendias and Pendias, 1992). The most important nickel mineral is pentlandite, and nickel occurs as a constituent of pyrrhotite and ferromagnesian minerals (Garrett, 1998). The range in Ni content of Canadian soils has been documented as 1-55 ppm with an average of 19 ppm (NRCC, 1981) but worldwide amounts seem to be much higher (1-450 ppm) (Kabata-Pendias and Pendias, 1992) with an average of 40 ppm (McGrath and Smith, 1990). While there are several oxidation states of Ni, only Ni^{2+} is stable in the soil environment (McGrath and Smith, 1990).

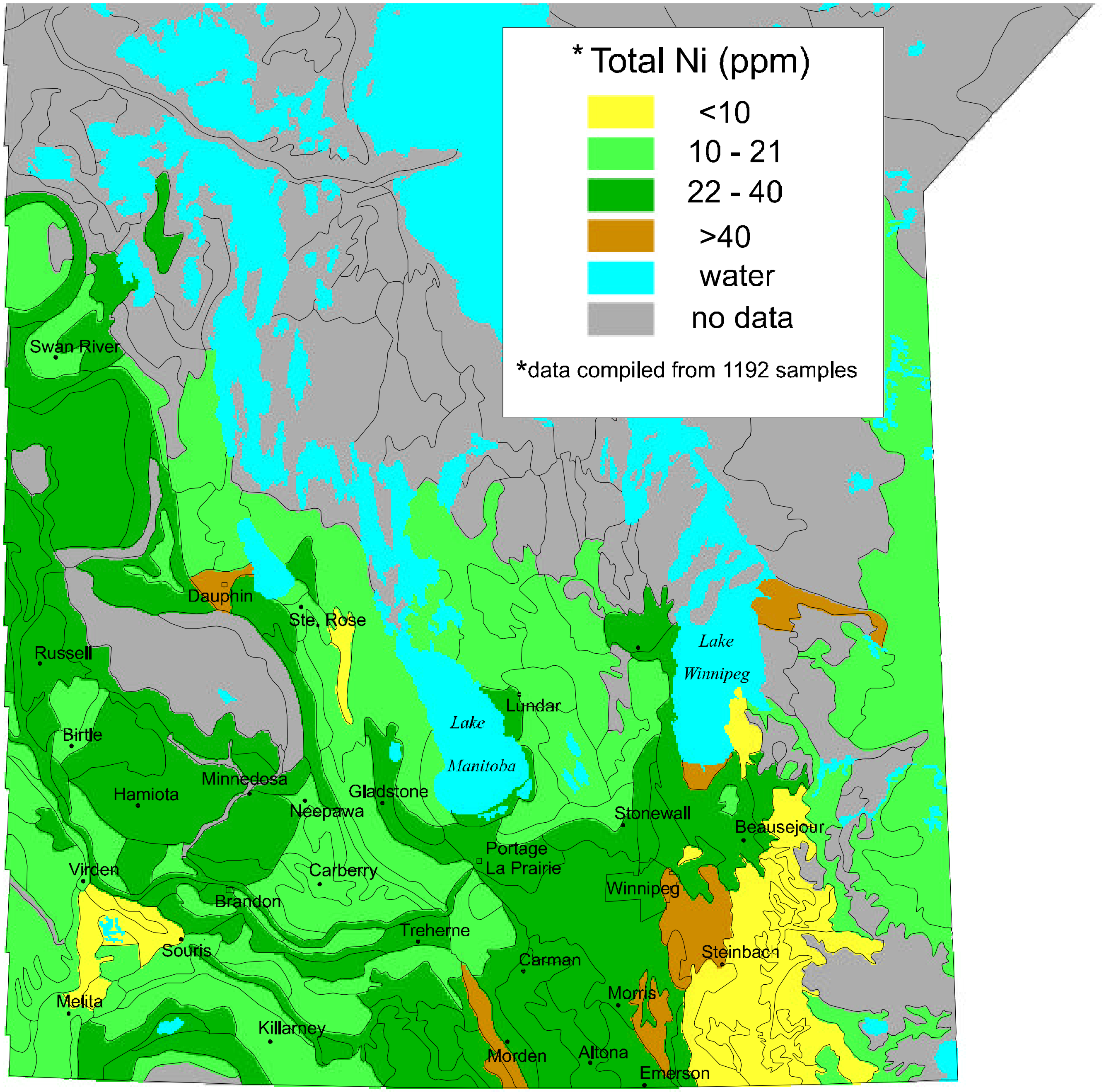
Nickel minerals will release Ni^{2+} upon weathering, which may precipitate with Fe and Mn oxides, or be adsorbed onto clay and organic fractions (Kabata-Pendias and Pendias, 1992). Ni bioavailability decreases as soil pH increases, and mobility will also be lower in soils with high cation exchange capacity (NRCC, 1981). In fact, the most available fraction of nickel in soil may be that associated with Fe and Mn oxides (Norrish, 1975). Nickel in solution exists primarily as Ni^{2+} which is readily mobile and available to plants (NRCC, 1981).

It has not been established that Ni is essential for plant growth, although it may be active in hydrogenase and translocation of nitrogen, and is known to be present in urease (Kabata-Pendias and Pendias, 1992). It is easily translocated within plants and accumulates in leaves and seeds (Kabata-Pendias and Pendias, 1992). Nickel is required for animals, and some instances of deficiency have been established (NRCC, 1981). It may also be essential for human health (McGrath and Smith, 1990). Deficiencies of Ni are unlikely to occur in plants or animals under natural conditions. If there is a nickel requirement for plants, it is thought to be very small and well met under natural conditions, while Ni intake levels in the animal diet are generally higher than levels shown to cause deficiencies (McGrath and Smith, 1990). Plants show symptoms of toxicosis at leaf levels of 10-100 ppm Ni (dry weight basis) and may exhibit chlorosis, gray-green leaves and stunted root and plant growth (Kabata-Pendias and Pendias, 1992). No guidelines have been established for the maximum allowable concentration of Ni in drinking water (CCREM, 1995).

The nickel content of Manitoba soils (Table 2, pg 47) ranges from 2 to 98 ppm with a median content of 21 ppm. These concentrations fall within the range established for soils on a world-wide basis. The Manitoba average is about one-half of the world average, but close to the average listed for Canadian soils. The nickel content of Manitoba soils is closely related to the texture of the soil material, increasing with increasing clay content from an average of 11 ppm in coarse-textured materials to 38 ppm in fine-textured materials (Table 4, pg 50). The geographic distribution of nickel in southern Manitoba soils is also influenced by lithology of the soil parent material. The highest concentrations of nickel (> 40 ppm) occur in landscapes of dominantly poorly drained clay soils in the Red River Plain (polygons 90 and 91) and imperfectly drained clay soils of the Dauphin Lake Plain (polygon 125). Along the Pembina Escarpment in southern Manitoba (polygons 64 and 72) (Table 5, pg 51) higher than average concentrations result from the influence of the shale materials which contribute to the high clay content of these soils. The shale bedrock, the source for most of these clay sediments, outcrops along the lower portions of the Manitoba Escarpment. This influence is reflected in many of the individual soils sampled in the escarpment area (Table 6, pg 57).

Total Nickel (Ni) in Manitoba Soils

Scale 1:3 000 000



Selenium - Se

Selenium is present mainly in organic rich sediments (0.4-0.6 ppm) and shales (0.6 ppm) and is low in all igneous rocks (0.01-0.05 ppm) (Kabata-Pendias and Pendias, 1992). The world-wide range of Se in soils is 0.005-1.9 ppm with an average of 0.33 ppm for surface soils (Kabata-Pendias and Pendias, 1992). Uncontaminated soils were previously considered to have had a selenium content of 0.01 ppm (Norrish, 1975). Se is present in the soil in numerous forms including selenides (Se^{2-}), elemental Se (Se^0), selenites (SeO_3^{2-}), selenates (SeO_4^{2-}), and organic Se compounds which are generally present in humus (Tisdale et al., 1985).

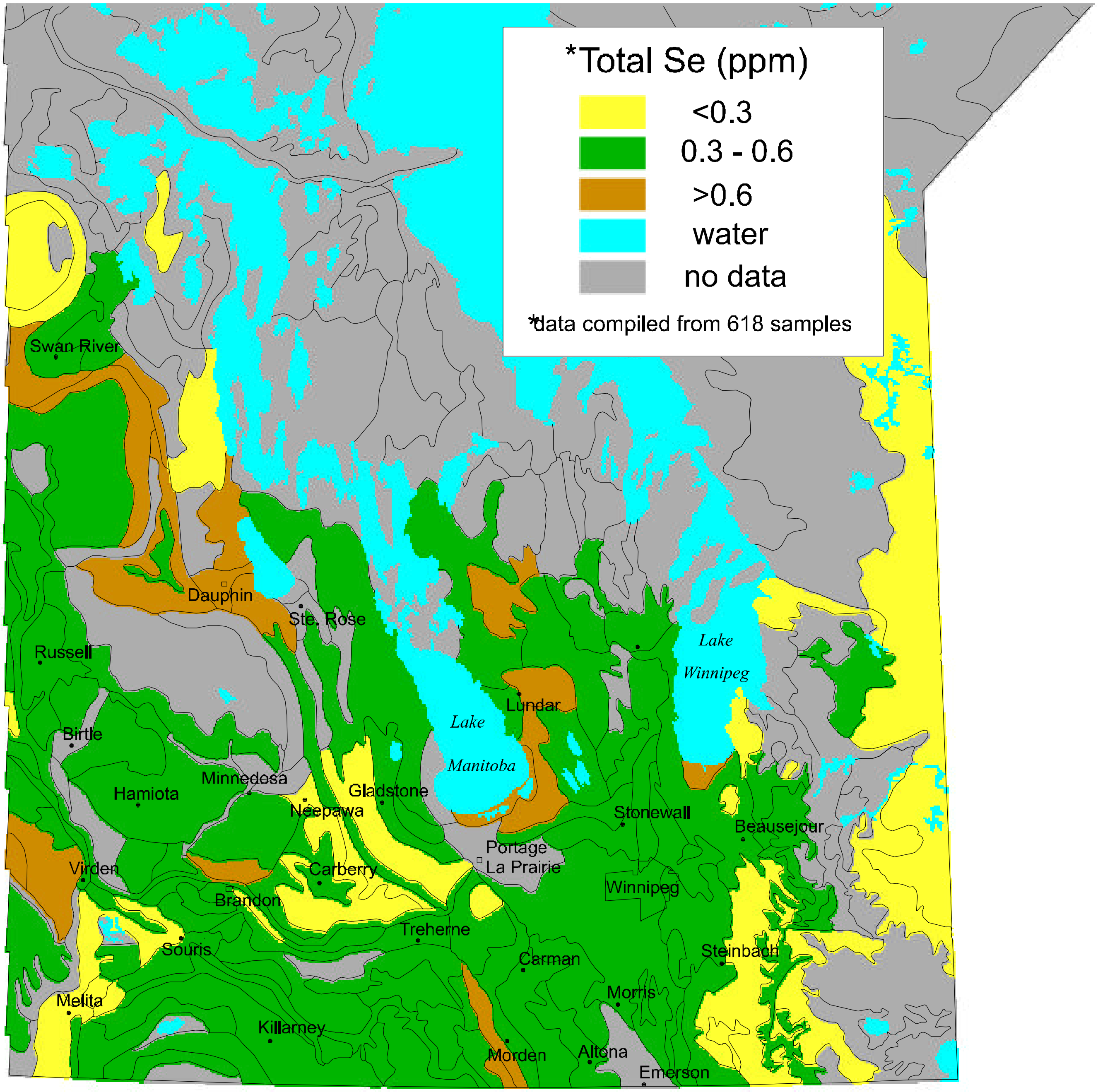
Selenium solubility in soil is controlled by oxidation conditions and pH (Kabata-Pendias and Pendias, 1992). Selenates (6+) compose the bulk of water-soluble Se, as they are highly soluble and available and are stable in basic oxidized soils (Tisdale et al., 1985). Selenites (4+) are also soluble in water but are only slightly available to plants (Tisdale et al., 1985). This is the only form of Se present in well drained, neutral mineral soils (Kabata-Pendias and Pendias, 1992). Insoluble selenides and Se sulfides are present in wet acid soils and soils high in organic matter; they are only slightly mobile and their availability for plant uptake is limited (Kabata-Pendias and Pendias, 1992). Se availability is modified by complexation, chelation and organic compounds and is very low in iron rich soils (Kabata-Pendias and Pendias, 1992).

Selenium is essential for some plants, but it has not been established as an essential element in general (Kabata-Pendias and Pendias, 1992). Ruminants require Se in their diet and can become deficient, leading to muscular dystrophy or "white muscle disease" if forages contain < 0.01 ppm Se on a dry weight basis (Kabata-Pendias and Pendias, 1992). Se is essential in humans, and can lead to cardiomyopathy and tubular bone changes if deficient (Kabata-Pendias and Pendias, 1992) although the level of requirement is unknown (Marier and Jaworski, 1983). Phytotoxicity is seldom observed under natural conditions, but will occur if the soil Se content is greater than 5 ppm (Kabata-Pendias and Pendias, 1992). If ruminants consume crops with Se contents greater than 0.1 ppm they can develop acute ("blind staggers") or chronic (alkali disease) selenium toxicosis (Kabata-Pendias and Pendias, 1992). Toxic levels in humans lead to malformation in children, miscarriage and dermatitis (Marier and Jaworski, 1983). The maximum allowable content of Se in water for human consumption is set at 0.01 ppm (CCREM, 1995).

The selenium content of Manitoba soils ranges from 0.1 to 3.8 ppm with a median content of 0.4 ppm (Table 2, pg 47). The concentrations observed in Manitoba soils are at the high end of the range established for soil on a world-wide basis, although 95% of the samples fall within the world range. Selenium, as with many other trace elements, follows a pattern of increasing concentration with increasing clay content. The lowest amounts of selenium occurred in the coarse-textured soils (an average content of 0.2 ppm) and Se content gradually increased with increasing clay content to 0.7 ppm in the fine-textured materials (Table 4, pg 50). The geographic distribution of selenium in Manitoba soils is also influenced by the origin and lithology of the soil parent material. The inclusion of shales, particularly acid weathering pyritiferous shales of the Keld Member, results in levels of selenium that are higher than the average for Manitoba soils (Table 5, pg 51). Several of the alluvial soils close to the Manitoba Escarpment area (Benton, Blumengart and Edward series, Table 6, pg 57), which contain shaly material washed into the parent material are also characterized by higher concentrations of Se.

Total Selenium (Se) in Manitoba Soils

Scale 1:3 000 000



Silver - Ag

Sources differ on the amounts of silver present in rocks but they agree that amounts are higher in organic rich shales (0.07-0.1 ppm) (Kabata-Pendias and Pendias, 1992). In soils, background levels are generally less than 0.1 ppm (Kabata-Pendias and Pendias, 1992), but the overall range of Ag in soils is 0.01-5.0 ppm (Alloway, 1990), with organic soils occupying the upper portion of the range (2-5 ppm) (Kabata-Pendias and Pendias, 1992). The average soil silver content is considered to be 0.1 ppm (Alloway, 1990), and contaminated soils have been found to contain levels of up to 10 ppm (Alloway, 1990). Minerals high in silver include argentite, proustite, pyrargyrite and cerargyrite (CCREM, 1995). In addition, due to isomorphic substitution, silver is often a component in minerals like galena and sphalerite (Alloway, 1990). It has oxidation states of 0 and 1+ in soil (Alloway, 1990).

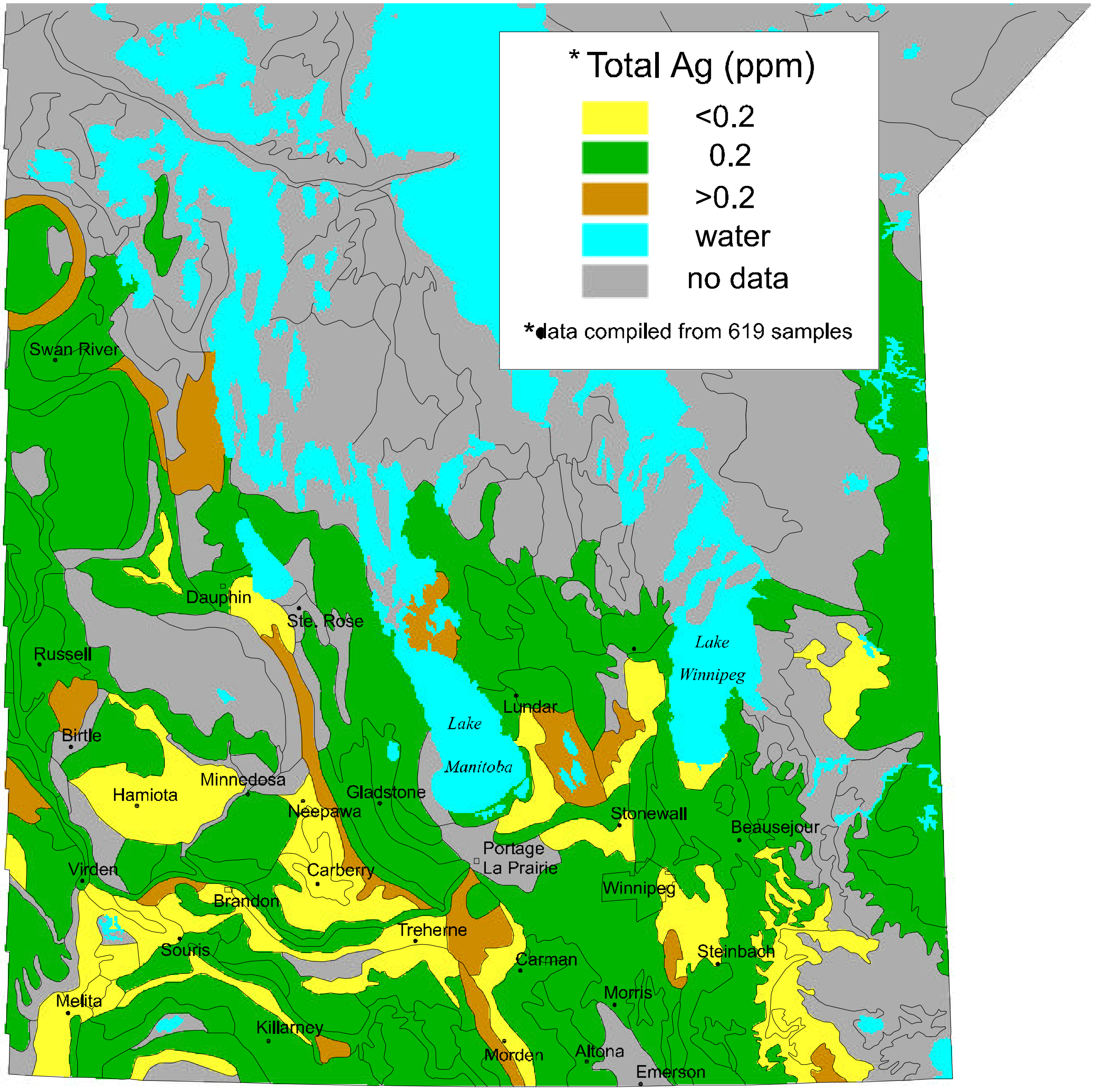
Silver in soils is controlled by pH, oxidation conditions and soil organic matter (Alloway, 1990). Mobile complexes of silver exist, but are immobile at pH > 4; alkaline and reduced soil can encourage precipitation of Ag (Kabata-Pendias and Pendias, 1992). Humic substances can adsorb and complex Ag (Kabata-Pendias and Pendias, 1992) and this is demonstrated in field soils by its accumulation in the surface horizons (Alloway, 1990), particularly in contaminated soils (Kabata-Pendias and Pendias, 1992). Leaching of Ag will be slow under these conditions because of the strong adsorption (Alloway, 1990). Therefore, the mobility of Ag in soil will increase with humus decomposition, which is inversely proportional to pH (Alloway, 1990). In addition, silver precipitation can be encouraged by soils high in S (Kabata-Pendias and Pendias, 1992) particularly under anaerobic conditions, where sulfides precipitate Ag into insoluble solids (McBride, 1994). While the organically bound silver fraction is a large proportion of the total soil Ag (Alloway, 1990), manganese oxides have been considered the most significant adsorbent of soil Ag (Kabata-Pendias and Pendias, 1992).

Silver has no known biological function, and is toxic to plants at dry weight levels of 5-10 ppm (Kabata-Pendias and Pendias, 1992). If present in high levels in plant tissue, silver may precipitate as Ag_2S or be reduced to metallic Ag, leading to tissue darkening (Alloway, 1990). It is relatively harmless to higher life forms (Alloway, 1990). The guideline for silver content in water used for human consumption is 0.05 ppm (CCREM, 1995).

The average silver content of Manitoba soils ranges from 0.1 to 1.8 ppm with both a mean and median content of 0.2 ppm (Table 2, pg 47). These concentrations are slightly above the average world-wide content of 0.1 ppm. Background levels of silver in Manitoba soils do not appear to vary with soil texture (Table 3 and 4, pg 48 and 50). The presence of shale debris in the soil parent material appears to contribute to higher silver concentrations in the soils close to the Manitoba Escarpment (Table 5, pg 51).

Total Silver (Ag) in Manitoba Soils

Scale 1:3 000 000



Vanadium - V

Vanadium is distributed uniformly throughout most soil profiles (Kabata-Pendias and Pendias, 1992) and the amounts in which it is present reflects the nature of the parent material on which the soil was formed. Mafic rocks have the highest vanadium content (200-250 ppm) followed closely by organic rich shales (80-130 ppm) (Kabata-Pendias and Pendias, 1992) so that soils formed from these materials will be comparatively high in vanadium. Vanadium is naturally present in the soil in amounts ranging from 18-115 ppm according to Kabata-Pendias and Pendias (1992), but there are values in the literature that are much higher and there seems to be little agreement on an average value. Soils that have been contaminated have been found to have concentrations higher than 100 ppm (Kabata-Pendias and Pendias, 1992), while other sources state that 100 ppm may be an average level (Jones et al, 1990).

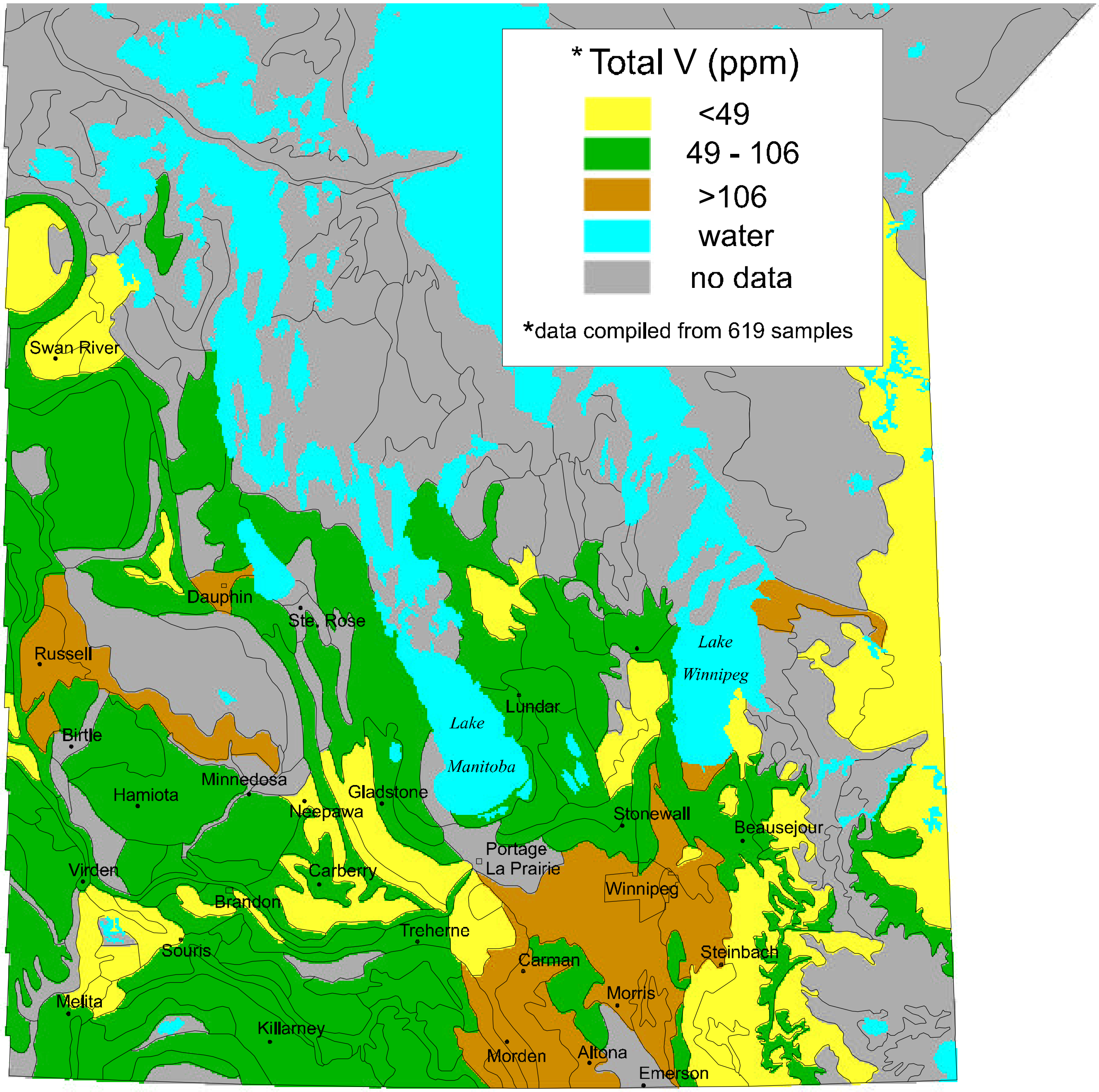
Important forms of vanadium in soil include vanadyl (VO^{2+}) and metavanate (VO^{3-}), both of which may be taken up by plants under normal conditions (Hopkins et al., 1977). Vanadium is most mobile and available in aerated alkaline and neutral soils whereas at low pH vanadyl cations predominate and are likely to complex with organic matter, Fe oxides and clay minerals (McBride, 1994; Kabata-Pendias and Pendias, 1992). It is basically immobile under reducing conditions (van Zinderen Bakker and Jaworski, 1980).

Vanadium is believed to be involved in N_2 fixation but it has not been proven to be essential for plants. It is essential for some animals but is not required by humans and can cause respiratory problems when present in the atmosphere in large amounts (van Zinderen Bakker and Jaworski, 1980). It may be required by plants at low levels (0.002 ppm) (Tisdale et al., 1985) and is phytotoxic in leaf concentrations of 5-10 ppm (Kabata-Pendias and Pendias, 1992). Levels required by animals for optimum growth are 0.05-0.5 ppm in food, but vanadium can be toxic in large amounts (van Zinderen Bakker and Jaworski, 1980). There is currently no guideline for the maximum allowable level of vanadium in drinking water in Canada (CCREM, 1995).

The vanadium content of Manitoba soils varies greatly, ranging from a minimum of 15 ppm to a maximum of 455 ppm (Table 2, pg 47). The median vanadium content is 76 ppm (Table 2, pg 47). Although the vanadium content of 75% of the samples was within the range accepted for soils on a world-wide basis, the maximum contents in Manitoba soils generally exceed the high end of the naturally occurring world-wide range. The vanadium content is strongly influenced by soil texture, gradually increasing with increasing clay content from 35 ppm in coarse-textured materials to 138 ppm in fine-textured soils (Table 3 and 4, pg 48 and 50). The vanadium content of southern Manitoba soils is also strongly influenced by the origin and lithology of the soil parent material. Soil landscapes above the Manitoba Escarpment in which the shale bedrock is close to the surface or in which inclusions of weathered shale make up a large portion of the parent material are characterized by a higher than average content of vanadium. There is also a large area encompassing Carman, Altona and Winnipeg which has a high V content. This is likely due to V complexation with clay minerals in the fine textured soils predominant in this area.

Total Vanadium (V) in Manitoba Soils

Scale 1:3 000 000



Zinc - Zn

The largest amounts of zinc are found in mafic rocks and organic-rich shales (both at 80-120 ppm); lower amounts are present in limestones and sandstones (10-30 ppm) (Kabata-Pendias and Pendias, 1992). The overall zinc content of soils ranges from 10-300 ppm (Tisdale et al., 1985) while background levels for uncontaminated soils are 17-125 ppm on a world wide basis (Kabata-Pendias and Pendias, 1992).

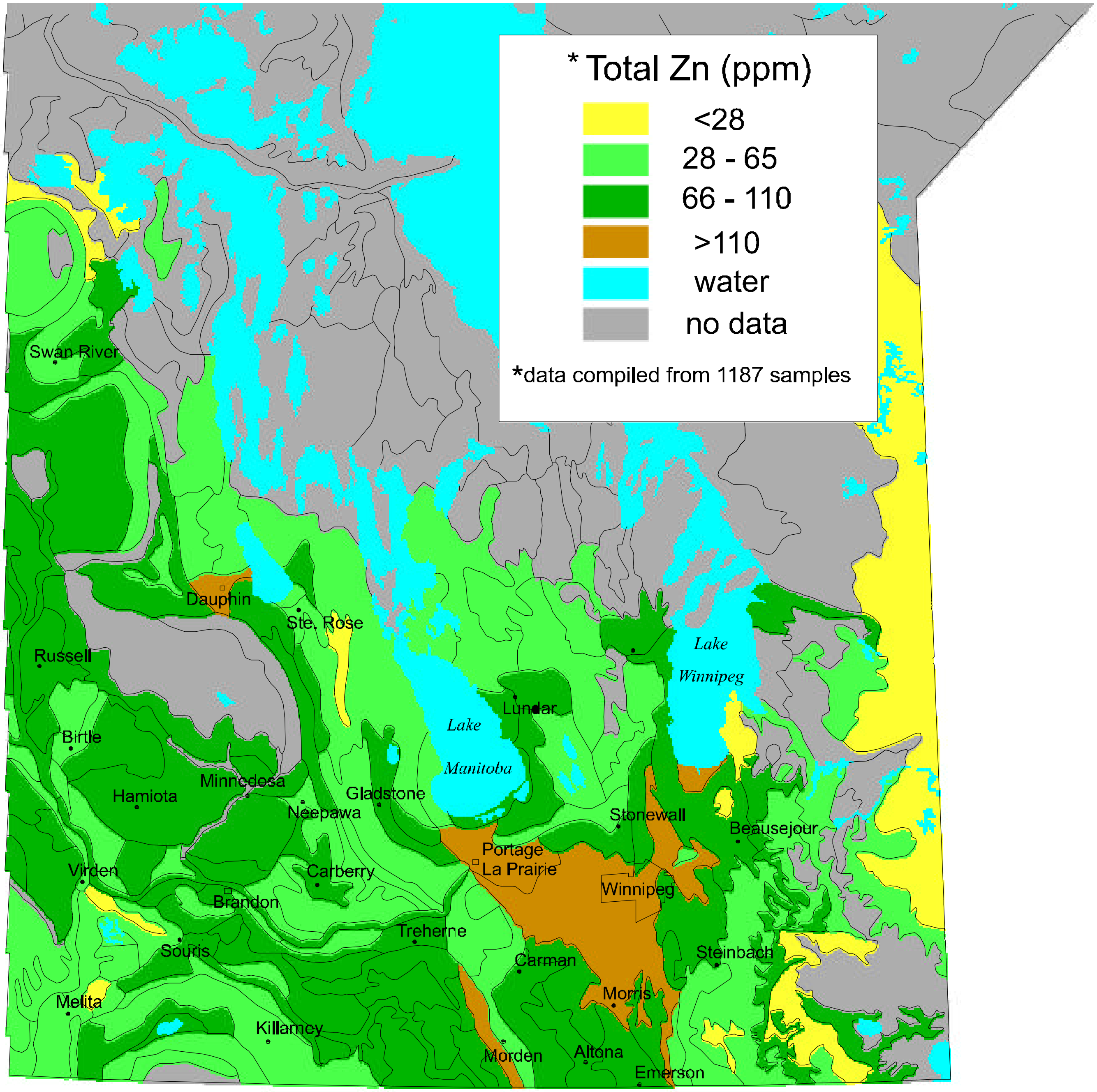
Weathering of zinc minerals leads to the release of Zn^{2+}, which is the most common and mobile zinc ion in soil (Kabata-Pendias and Pendias, 1992) and the main form utilized by plants (Kiekens, 1990). Zinc is adsorbed by clay and organic matter and may accumulate in the surface horizons of soil (Kabata-Pendias and Pendias, 1992). Zinc solubility in soil is high compared to other trace elements. It is controlled by the presence of clay minerals and hydrous oxides and affected by pH (Kabata-Pendias and Pendias, 1992). At $pH<7$ there is less adsorption of Zn^{2+}, which may result in leaching from sandy soils (Kabata-Pendias and Pendias, 1992). At high soil pH, the formation of insoluble compounds ($Zn(OH)_2$ and $ZnCO_3$) may restrict Zn availability (Tisdale et al., 1985). As a result, deficiencies are likely to be found under the following soil conditions: strongly acid or alkaline, low organic matter, free $CaCO_3$ and high N and P (Kabata-Pendias and Pendias, 1992).

Zinc is essential for plants in lipid and carbohydrate metabolism and is required at levels of 10-20 ppm (Kabata-Pendias and Pendias, 1992). It is required for several enzymes in animals (Scott, 1972) and is also essential for energy metabolism in humans (Kiekens, 1990). A clear relationship between plant and animal deficiency does not exist because livestock deficiencies may be a result of inefficient digestion, rather than an overall lack of zinc in diet (Kubota and Alloway, 1972). In fact, animals fed a diet of zinc deficient plants should have their dietary requirements met (Kubota and Alloway, 1972). Phytotoxicity occurs at leaf levels of 100-400 ppm (Kabata-Pendias and Pendias, 1992). The maximum allowable concentration of zinc in water for human consumption is 5.0 ppm based on aesthetic considerations (CCREM, 1995).

The zinc content of soils in southern Manitoba ranges from 8 to 230 ppm with a median content of 65 ppm (Table 2, pg 47). These concentrations fall within the range in concentration for zinc in soil established on a world-wide basis. The zinc content is strongly influenced by soil texture (Table 4, pg 50). As clay content increases, the average concentration of zinc gradually increases from 32 ppm in coarse-textured soils to 105 ppm in fine-textured soils such as those of the Red River Plain (polygons 89 and 99) and the Dauphin Lake Plain (polygon 125) (Table 5, pg 51). The zinc content of soil is also influenced by the lithologic character of the soil parent material. Landscapes along the Manitoba Escarpment underlain by shale close to, or at the surface, contain shale materials that result in average zinc concentrations that exceed the median values for Manitoba soils (Table 5, pg 51).

Total Zinc (Zn) in Manitoba Soils

Scale 1:3 000 000



SUMMARY

The wide range in concentration of total trace elements observed in this study reflects the interaction of at least two factors:

1) the varied nature of the physical and chemical composition of soil parent materials, and
2) the provenance or source of the mineralogic contribution to the soil parent material.

The levels of trace elements studied were generally within the world-wide range given for soils. However, selenium and molybdenum were found to be present in some Manitoba soils in amounts exceeding the higher end of the world range, and the maximum level of vanadium (found in Manitoba soils) was at the high end of the world-wide range. Trace elements examined in this study that are potentially highly toxic to biological systems and therefore of environmental concern are within reported levels of acceptability.

Soil texture has a major influence on the total concentration of selected trace elements in soil. Analysis of a wide range of soils in this study indicates that total trace element content in the surface horizons of Manitoba soils is generally lowest in sandy soils and highest in clayey soils. Specifically, total Fe, Cu, Co, Ni, V and Zn concentration is strongly related to clay content. In addition, highest levels of these elements tend to be associated with soils in close proximity to Cretaceous shale bedrock or soils having abundant inclusions of shaly material in the parent material. Samples from polygons 72 and 125 demonstrate that shale bedrock influences soil parent materials in close association with the Manitoba Escarpment resulting in elevated levels of As, Cd, Cr, Mn, Hg, Ni, Se, Ag, V and An. Elements that are most strongly related to fine textured soils tend to have low concentrations in those polygons low in clay content, ie. polygons 20, 83 and 101 exhibit low concentration values for Cu, Ni and Zn. Clay content, therefore can be used to estimate the total content of these elements in soil. The concentration of other elements such as Mn, Zn, Pb and Ni, although related to clay content, appears to be influenced by additional factors such as mineralogy of soil parent material, soil moisture regime and characteristics of the ground water. Vanadium exhibited a strong relationship with both soil texture and parent

The data from this study provide a preliminary assessment of the background levels of selected trace elements in Manitoba soils. The concentration of total Fe, Mn, Zn, Cu and Co can be used to identify those soils which may exhibit trace element deficiency or excess for crop growth and subsequent nutritional imbalances for animals consuming those crops. The total concentration of trace elements in soils also provides baseline data for assessing the potential loading capacity of soils for the application of sewage sludge and other materials containing trace elements.

REFERENCES

Alloway, B. J. 1990. Cadmium. In Heavy Metals in Soils. B. J. Alloway (ed.). Blackie and Son, Ltd., Bishopbriggs, Glasgow. pp 100-124.

Boila, R. J., Devlin, T. J., Drysdale, R. A. and Lillie, L. E. 1984. Geographical variation in the copper and molybdenum contents of forages grown in northwestern Manitoba. Can. J. Animal Sci. 64: 899-918.

Boila, R. J., Devlin, T. J., Drysdale, R. A. and Lillie, L. E. 1985. Geographical variability of the zinc, manganese and iron concentrations of forages grown in northwestern Manitoba. Can. J. Animal Sci. 65: 861-870.

Bostock, H. S. 1970. Physiographic subdivisions of Canada. Geological Survey of Canada, Economic Geology Report No. 1. pp 10-32.

Canada Soil Inventory. 1989. Soil landscapes of Canada - Manitoba. Land Resource Research Centre, Research Branch, Agriculture Canada, Ottawa, Ont. Agric. Can. Publ. 5242/B. 22 pp. 1:1 million scale map compiled by Canada-Manitoba soil survey.

Carter, M. R. (ed.). 1993. Soil Sampling and Methods of Analysis. Lewis Publishers, CRC Press, Inc., Boca Raton, Florida. 823 pp.

CCREM. 1995. Canadian Water Quality Guidelines. March 1987. Canadian Council of Resource and Environment Ministers. Environment Canada, Ottawa.

Davies, B. E. 1990. Lead. In Heavy Metals in Soils, B. J. Alloway (ed.). Blackie and Son Ltd., Bishopbriggs, Glasgow. pp 177-196.

Dudas, M. J. and Pawluk, S. 1977. Heavy metals in cultivated soils and in cereal crops in Alberta. Can. J. Soil Sci. 57: 329-339.

Dunn, C. E. 1990. Saskatchewan Geol. Surv. Misc. Rept. 90-4: 193-197.

FAO Soils Bulletin 65. 1992. Status of Cadmium, Lead, Cobalt and Selenium in Soils and Plants of Thirty Countries.

Faust, S. D. and Aly, O. M. 1981. Chemistry of Natural Waters, Ann Arbor Science. 400 pp.

Garrett, R. G. 1998. Personal communication.

Gupta, U. C. 1986. Manganese nutrition of cereals and forages in Prince Edward Island. Can. J. Soil Sci. **66**: 59-65.

Gupta, U.C. and J. Lipsett. 1981. Molybdenum in Soils, Plants and Animals. Advances in Agronomy. 34:73-115.

Haluschak, P. and Russell, A. 1971. Total minor element content of soils in the Portage map area of Manitoba. Pages 4-9 in Proc. 15th Annual Manitoba Soil Sci. Meet.

Hopkins, L. L., Cannon, H. L., Musch, A. T., Welch, R. M., and Nielson, F. H. 1977. Vanadium. Geochem. Environ. 2:93-107. (Cited in van Zinderen Bakker and Jaworski 1980).

Jones, J. B. Jr. 1972. Plant Tissue Analysis for Micronutrients. In Micronutrients in Agriculture. J.J. Mortvedt, P.M. Giordano and W.L. Lindsay (eds.). Soil Science Society of America, Inc., Madison, Wisconsin. pp 331-336.

Kabata-Pendias, A. and Pendias, H. 1992. Trace Elements in Soils and Plants, 2nd ed., CRC Press, Inc., Boca Raton, Florida. 365 pp.

Kiekens, L. 1990. Zinc. In Heavy Metals in Soils. B.J. Alloway (ed.). Blackie and Son Ltd., Bishopbriggs, Glasgow. pp. 261-279.

Kruger, G. A., Karamanos, R. E. and Singh, J. P. 1985. The copper fertility of Saskatchewan soils. Can. J. Soil Sci. **65**: 89-99.

Kubota, J. 1964. Cobalt content of New England soils in relation to cobalt levels in forages for ruminant animals. Soil Sci. Soc. Amer. Proc. 28:246-251.

Kubota, J. and Allaway, W. H. 1972. Geographic Distribution of Trace Element Problems. In Micronutrients in Agriculture, Soil Science Society of America, Inc., Madison, Wisconsin. pp 525-592.

Lagerwerff, J. V. 1972. Lead, Mercury, and Cadmium as Environmental Contaminants. In Micronutrients in Agriculture, Soil Science Society of America, Inc., Madison, Wisconsin. pp 596-636.

Lee Tan and Yao Chi-Lung. 1970. Intl. Geol. Review **12**(7):778-786.

Madden, J. 1974. Clay mineralogy and heavy metals in soils and geological sediments of Manitoba. Pages 27-41 in Proc. 18th Annual Manitoba Soil Sci. Meet.

Marier, J. R. and Jaworski, J. F. 1983. Interactions of Selenium. Associate Committee on Scientific Criteria for Environmental Quality, National Research Council of Canada, Ottawa. NRCC No. 20643. 84 pp.

McBride, M. B. 1994. Environmental Chemistry of Soils. Oxford University Press, Inc. New York, New York. pp 326-339.

McGrath, S. P. and Smith, S. 1990. Chromium and Nickel. In Heavy Metals in Soils. B.J. Alloway (ed.). Blackie and Son, Ltd., Bishopbriggs, Glasgow. pp 151-176.

McKeague, J. A., Desjardins, J. G. and Wolynetz, M. S. 1979. Minor elements in Canadian soils. Research Branch, Agriculture Canada, Ottawa, Ont. LRRI Contribution No. 27.

McKenzie, R. M. 1975. Mineralogy and Chemistry of Soil Cobalt. In Trace Elements in Soil-Plant-Animal Systems. D.J.D. Nicholas and A.R. Egan, (eds.). Academic Press, Inc. New York. pp 83-94.

McLennan, S. M. 1992. In Encyclopedia of Earth Sciences, Vol. 1. W. A. Nierenberg, (ed.). Pp 581-592.

Mills, J. G. and Zwarich, M. A. 1975. Heavy metal content of agricultural soils in Manitoba. Can. J. Soil Sci. **55**: 295-300.

NAS/NAE. 1973. Water Quality Criteria 1972. Report of the U.S. National Academy of Sciences and National Academy of Engineering. Funded by U.S. Environmental Protection Agency, Washington D.C. EPA-R3-73-033. (Cited in CCREM 1995).

Nicholas, D. J. D. 1975. The Functions of Trace Elements in Plants. In Trace Elements in Soil-Plant-Animal Systems, D.J.D. Nicholas and A.R. Egan, Eds. Academic Press, Inc., New York. pp 181-198.

Norrish, K. 1975. The Geochemistry and Mineralogy of Trace Elements. In Trace Elements in Soil-Plant-Animal Systems, D.J.D. Nicholas and A.R. Egan, Eds. Academic Press, Inc., New York. pp 55-82.

NRCC. 1976. Effects of Chromium in the Canadian Environment. Associate Committee on Scientific Criteria for Environmental Quality, National Research Council of Canada, Ottawa. NRCC No. 15017. 168 pp.

NRCC. 1978a. Effects of Lead in the Environment - Quantitative Aspects. Associate Committee on Scientific Criteria for Environmental Quality, National Research Council of Canada, Ottawa. NRCC No. 16736. 779 pp.

NRCC. 1978b. Effects of Arsenic in the Canadian Environment. Associate Committee on Scientific Criteria for Environmental Quality, National Research Council of Canada, Ottawa. NRCC No. 15391. 349 pp.

NRCC. 1979. Effects of Mercury in the Canadian Environment. Associate Committee on Scientific Criteria for Environmental Quality, National Research Council of Canada, Ottawa. NRCC No. 16739. 290 pp.

NRCC. 1981. Effects of Nickel in the Canadian Environment. Associate Committee on Scientific Criteria for Environmental Quality, National Research Council of Canada, Ottawa. NRCC No. 18568. 352 pp.

Scott, M. L. 1972. Trace Elements in Animal Nutrition. In Micronutrients in Agriculture, Soil Science Society of America, Inc., Madison, Wisconsin. pp 555-592.

Singh, B.R. and Steinnes, E. 1994. Soil and water contamination by heavy metals. In Soil Processes and Water Quality. Advances in Soil Science 1994. R. Lal and B.A. Stewart, (eds.). Lewis Publishers, CRC Press, Inc., Boca Raton, Florida. pp. 233-270.

Spiers, G. A., Dudas, M. J. and Turchenek, L. W. 1989. The chemical and mineralogical composition of soil parent materials in northeast Alberta. Can. J. Soil Sci. **69**: 721-737.

SPSS Inc. 1989. The Power of Statistical Analysis for dBaseIII PLUS^{TM} and dBase IV Users^{TM}. Tate Publishing, a Division of Ashton-Tate Corporation, 20101 Hamilton Avenue, Torrance, CA90502-1319.

Steinnes, E. 1990. Mercury. In Heavy Metals in Soils. B.J. Alloway (ed.). Blackie and Son Ltd., Bishopbriggs, Glasgow. pp 222-236.

Taylor, S. R. 1964. Abundance of chemical elements in the continental crust. Geochem. Cosmochem. Acta **28**(8): 1273-1285.

Tisdale, S. L., Nelson, W. L. and Beaton, J. D. 1985. Soil Fertility and Fertilizers. 4th ed. MacMillan Publishing Co. New York. pp 358-403.

Turekian, K. K. and Wedepohl, K. H. 1961. Bull. Geol. Soc. Am. **72**(1):175-192.

van Zinderen Bakker, E. M. and Jaworski, J. F. 1980. Effects of Vanadium in the Canadian Environment. Associate Committee on Scientific Criteria for Environmental Quality, National Research Council of Canada, Ottawa. NRCC No. 18132. 94 pp.

Vine, J. D. And Tourtelot, E. B. 1970. Econ. Geol. **65**(3):253-272.

Webb, J. S. and Howarth, R. J. 1979. Regional geochemical mapping. Phil. Tran. R. Soc. Lond. Sel. B. 288: 81-93.

Webber, M. D. and Shamess, A. 1987. Heavy metal concentration in Halton Region soils: An assessment for future municipal utilization. Can. J. Soil Sci. **67**: 893-903.

Zwarich, M. A. and Mills, J. G. 1979. Effects of sewage sludge application on the heavy metal content of wheat and forage crops. Can. J. Soil Sci. **59**: 231-239.

APPENDIX

Abbreviations

ppb	parts per billion
ppm	parts per million
SD	standard deviation
COS	coarse sand
MS	medium sand
FS	fine sand
VFS	very fine sand
LCOS	loamy coarse sand
LS	loamy sand
LFS	loamy fine sand
LVFS	loamy very fine sand
COSL	coarse sandy loam
MSL	medium sandy loam
FSL	fine sandy loam
VFSL	very fine sandy loam
L	loam
SCL	sandy clay loam
CL	clay loam
SIL	silt loam
SICL	silty clay loam
SC	sandy clay
SIC	silty clay
C	clay
HC	heavy clay

Table 2. Summary statistics for trace elements

	Ag ppm	As ppm	Cd ppm	Co ppm	Cr ppm	Cu ppm	Fe %	Hg ppb	Mn ppm	Mo ppm	Ni ppm	Pb ppm	Se ppm	V ppm	Zn ppm
N	619	206	619	1228	206	1227	1228	619	1226	619	1192	1193	618	619	1187
Mean	0.2	6.6	0.2	14	51	19	2.02	60	651	3.2	23	17	0.5	83	68
SD	0.1	4.6	0.5	6	25	10	0.85	35	421	2.3	13	9	0.4	49	33
Minimum	0.1	0.3	0.1	2	13	1	0.17	10	24	1	2	3	0.1	15	8
5th centile	0.1	1.4	0.1	5	20	5	0.8	10	210	1	7	7	0.1	27	22
10th centile	0.1	2.3	0.1	6	24	7	0.98	20	271	2	9	8	0.1	33	27
25th centile	0.1	4.2	0.1	9	31	12	1.4	30	395	2	13	11	0.2	48	43
Median	0.2	5.8	0.1	12	46	18	1.96	50	572	3	21	15	0.4	76	65
75th centile	0.2	7.6	0.2	17	65	25	2.5	90	792	4	29	23	0.6	106	87
90th centile	0.3	12	0.3	22	85	35	3.2	110	1041	5	40	30	0.9	144	110
95th centile	0.4	15.3	0.5	27	101	39	3.7	120	1339	5	46	34	1.2	159	128
Maximum	1.8	28.5	7.9	37	142	68	5	210	5200	31	98	55	3.8	455	230
Soils of the Interior Plains[1]															
N	-	-	-	51	51	51	49	45	48	-	51	50	54	-	49
Mean	-	-	-	16	40	23	2	72	378	-	21	16	0.4	-	66
Minimum	-	-	-	6	5	1	0.5	6	95	-	2	9	0.05	-	10
Maximum	-	-	-	28	76	46	4.2	770	1120	-	42	38	2.2	-	140

[1] McKeague et al, 1979.

Table 3. Mean total trace element content of soils by texture

Textural Class	N	Ag±sd ppm	N	As±sd ppm	N	Cd±sd ppm	N	Co±sd ppm	N	Cr±sd ppm	N	Cu±sd ppm	N	Fe±sd %	N	Hg±sd ppb
COS	11	0.2±0.1	8	4±2	11	0.1±.0	13	6±2	8	25±9	13	9±3	13	1.45±0.56	11	25±17
MS	26	0.1±0.1	5	4±1	26	0.1±0.1	46	7±3	5	22±6	46	6±2	46	0.99±0.32	26	37±33
FS	28	0.1±0.1	12	3±1	28	0.1±0.1	47	7±3	12	25±4	47	6±2	47	1.05±0.33	28	45±40
VFS	2	0.2±0.1	1	4±0	2	0.1±.0	4	7±3	1	27±0	4	7±2	4	1.11±0.27	2	35±21
LCOS	13	0.2±0.1	7	27±1.5	13	0.1±.0	20	9±4	7	27±15	20	9±5	20	1.43±0.45	13	36±30
LS	10	0.2±0.1	2	4±1	10	0.1±.0	24	10±3	2	32±6	24	10±6	24	1.24±0.37	10	51±32
LFS	23	0.2±0.1	9	4±2	23	0.2±0.1	60	9±3	9	26±6	60	7±3	60	1.04±0.28	23	41±32
LVFS	2	0.2±0.1	1	12±0	2	0.1±0.0	9	11±2	1	53±0	9	9±5	9	1.27±0.72	2	50±0
COSL	7	0.2±0.1	5	5±3	7	0.1±0.1	13	12±5	5	39±21	13	13±3	13	1.85±0.30	7	46±33
MSL	14	0.2±.0	1	5±0	14	0.1±0	40	11±4	1	28±0	40	11±5	40	1.34±0.46	14	64±32
FSL	34	0.2±0.1	12	4±2	34	0.1±0.1	72	11±4	12	31±7	72	12±4	72	1.37±0.40	34	51±38
VFSL	22	0.2±0.1	8	6±2	22	0.2±0.1	46	10±3	8	37±4	46	12±4	46	1.36±0.42	22	49±34
L	83	0.2±0.1	24	6±2	83	0.1±0.1	210	14±5	24	46±8	210	18±4	210	1.97±0.37	83	62±31
SCL	41	0.2±0.1	10	5±2	41	0.2±0.1	86	12±4	10	40±12	86	16±4	86	1.71±0.46	41	60±30
CL	119	0.2±0.1	27	7±3	119	0.2±0.2	216	14±5	27	50±8	216	22±5	216	2.16±0.40	119	71±33
SIL	14	0.2±0.1	10	5±3	14	0.1±0.1	20	11±6	10	45±11	20	19±5	20	2.07±0.61	14	46±35
SICL	22	0.2±0.1	9	10±6	22	0.2±0.2	42	16±5	9	60±15	42	26±7	42	2.51±0.56	22	72±42
SC	-	-	-	-	-	-	3	22±7	-	-	3	21±1	3	1.79±0.31	-	-
SIC	25	0.2±0.1	13	10±7	25	0.2±0.3	46	18±6	13	75±15	46	30±5	46	2.93±0.63	25	59±24
C	55	0.2±0.2	20	12±7	55	0.5±1.0	95	17±7	20	76±23	95	30±7	95	2.75±0.59	55	73±37
HC	68	0.2±0.1	22	8±4	68	0.4±1.1	116	22±9	22	92±16	115	38±6	116	3.56±0.53	68	72±33

Table 3. Mean total trace element content of soils by texture - continued

Textural Class	N	Mn±sd ppm	N	Mo±sd ppm	N	Ni±sd ppm	N	Pb±sd ppm	N	Se±sd ppm	N	V±sd ppb	N	Zn±sd ppm
COS	13	943±1395	11	2±1	13	12±5	13	11±7	11	0.1±.0	11	35±12	13	33±19
MS	46	330±156	26	2±1	45	10±7	45	11±4	26	0.2±.1	26	28±8	45	27±13
FS	47	268±107	28	2±1	45	9±4	45	11±5	28	0.1±.1	28	35±9	47	28±12
VFS	4	435±139	2	2±1	4	10±2	4	12±5	2	0.1±.0	2	36±2	4	26±5
LCOS	20	619±287	13	2±1	19	11±4	20	15±7	13	0.3±.1	13	34±9	20	42±19
LS	24	486±182	10	2±1	24	11±3	24	16±5	10	0.2±.1	10	43±14	23	41±13
LFS	60	321±98	23	2±1	55	12±10	55	13±5	23	0.2±.2	23	39±10	57	34±13
LVFS	9	348±112	2	3±1	9	15±8	9	16±5	2	0.2±.1	2	74±28	9	39±16
COSL	13	873±383	7	2±0	13	16±4	13	14±4	7	0.5±.4	7	77±62	13	63±11
MSL	40	566±360	14	3±1	37	14±10	37	15±7	14	0.4±.1	14	52±20	38	47±16
FSL	72	518±341	34	2±1	72	14±5	72	16±8	33	0.3±.2	34	49±17	70	46±16
VFSL	46	416±133	22	3±1	43	14±4	43	16±8	22	0.3±.2	22	55±14	46	43±13
L	210	741±311	83	3±1	201	21±6	201	18±8	83	0.4±.3	83	73±21	210	67±20
SCL	86	615±364	41	3±1	84	19±9	84	17±8	41	0.5±.3	41	69±19	86	65±30
CL	214	832±363	119	4±1	211	25±7	211	17±8	119	0.5±.3	119	89±24	212	80±23
SIL	20	619±357	14	4±2	18	21±6	18	13±5	14	0.3±.2	14	71±26	20	59±24
SICL	42	825±390	22	4±2	40	27±8	40	20±12	22	0.5±.5	22	101±34	41	89±33
SC	3	481±37	-	-	3	40±14	3	19±8	-	-	-	-	2	91±29
SIC	46	735±283	25	5±5	45	35±12	45	20±9	25	0.7±.8	25	122±33	41	96±26
C	95	712±460	55	5±5	95	35±13	95	20±9	55	0.8±.6	55	130±68	89	99±30
HC	116	710±623	68	4±2	116	42±11	116	23±10	68	0.6±.5	68	151±49	101	115±29

Table 4. Mean total trace element content of soils in 5 textural groups

Textural Group	N	Ag±sd ppm	N	As±sd ppm	N	Cd±sd ppm	N	Co±sd ppm	N	Cr±sd ppm	N	Cu±sd ppm	N	Fe±sd %	N	Hg±sd ppb
Coarse	110	0.2±0.1	42	4±1	110	0.1±0.1	209	8±3	42	25±8	209	7±4	209	1.11±0.37	110	40±33
Moderately Coarse	58	0.2±0.1	19	4±2	58	0.1±0.1	137	11±4	19	33±12	137	11±4	137	1.38±0.43	58	53±33
Medium	118	0.2±0.1	41	6±2	118	0.2±0.1	275	13±5	41	44±9	275	17±4	275	1.87±0.46	118	58±33
Moderately Fine	181	0.2±0.1	45	7±4	181	0.2±0.2	343	14±5	45	50±12	343	21±6	343	2.09±0.50	181	69±34
Fine	147	0.2±0.2	54	10±6	147	0.4±1.0	259	19±8	54	83±20	258	33±8	259	3.14±0.69	147	70±34

Table 4. (Continued)

Textural Group	N	Mn±sd ppm	N	Mo±sd ppm	N	Ni±sd ppm	N	Pb±sd ppm	N	Se±sd ppm	N	V±sd ppm	N	Zn±sd ppm
Coarse	209	397±406	110	2±1	200	11±7	201	13±5	110	0.2±0.1	110	35±10	204	32±15
Moderately Coarse	137	512±354	58	3±1	134	14±7	134	16±7	57	0.4±0.2	58	53±27	133	47±17
Medium	275	679±317	118	3±1	261	20±6	261	18±8	118	0.4±0.3	118	69±21	275	62±21
Moderately Fine	341	779±378	181	3±1	334	24±8	334	18±8	181	0.5±0.3	181	86±26	338	77±26
Fine	259	710±514	147	4±4	258	38±13	258	21±10	147	0.7±0.6	147	138±56	232	105±30

Table 5. Summary of mean trace element contents data for soil landscape polygons

SLC Polygon*	N	Fe %	Mn ppm	Zn ppm	Cu ppm	Co ppm	Pb ppm	Ni ppm
1	3	1.10	486	36	7	14	11	11
2	4	1.39	635	51	8	14	20	9
3	6	1.94	763	71	18	18	21	21
4	3	1.86	808	73	16	18	17	17
5	5	2.02	723	71	19	14	16	21
6	8	1.24	621	44	9	8	16	11
7	5	1.13	640	40	8	8	17	11
8	3	2.21	811	89	22	17	29	33
9	12	2.31	727	66	21	13	12	24
11	3	2.47	844	77	23	14	12	28
13	2	1.76	1315	30	9	8	6	19
14	5	2.63	1568	50	17	13	11	28
15	1	0.45	170	8	1	3	-	-
17	11	1.29	584	34	8	10	11	12
18	3	2.39	586	58	16	12	14	19
19	7	1.25	501	39	7	12	16	8
20	7	1.06	310	34	7	9	12	11
21	4	0.92	349	34	6	13	18	9
22	7	2.76	892	96	22	19	19	29
24	3	0.82	393	26	3	11	11	6
25	3	1.32	820	44	7	18	10	14
26	2	2.30	773	75	23	9	12	23
27	3	1.81	1014	64	18	13	18	20
29	8	1.99	772	78	19	16	16	25
30	9	1.59	801	55	11	10	11	15
31	9	2.37	806	103	24	17	16	28
32	11	1.98	806	96	18	16	21	22
33	10	1.25	521	43	11	9	11	13
34	5	1.03	309	27	5	9	14	9
35	5	1.17	291	33	6	10	13	11
36	6	2.09	778	80	19	18	21	21
37	11	1.87	770	65	15	17	20	20
38	5	1.95	812	65	16	18	23	22
39	3	1.87	806	78	17	19	24	25
40	5	2.16	627	58	18	15	16	21
42	7	2.01	872	65	16	15	18	18
43	9	1.96	1305	81	17	17	17	22
44	17	2.11	861	67	16	14	16	21
45	6	2.18	719	69	20	16	14	22
46	7	1.34	552	34	15	10	16	8
47	10	2.08	708	73	17	15	18	23
49	6	2.01	759	75	18	16	17	22
50	7	1.70	778	57	15	15	16	19
51	5	2.46	487	62	25	19	29	21
52	6	2.21	1188	88	19	22	20	25
53	15	1.99	753	74	22	13	15	23
54	2	2.16	598	74	23	19	42	22
55	9	1.40	435	46	11	10	12	13
56	22	1.33	446	37	9	9	13	14
57	4	1.35	470	36	9	9	10	11

Table 5. Summary of mean trace element contents data for soil landscape polygons - continued

SLC Polygon*	N	Fe %	Mn ppm	Zn ppm	Cu ppm	Co ppm	Pb ppm	Ni ppm
58	22	1.91	569	55	12	8	12	16
59	27	2.14	540	69	18	10	15	20
60	3	2.52	1064	94	26	23	26	34
61	2	1.79	600	61	20	13	17	19
62	14	1.79	1086	94	17	14	18	21
63	21	2.23	1004	87	19	13	15	28
64	9	2.51	2019	106	27	18	19	50
65	2	1.98	901	85	20	20	20	22
66	29	2.05	1045	74	19	11	12	23
67	14	2.32	1152	99	26	13	15	31
68	28	2.04	986	82	21	11	12	24
69	11	3.50	661	104	37	28	29	40
70	10	2.57	723	91	29	19	21	33
71	3	3.93	407	110	35	24	21	42
72	18	2.67	1349	122	34	14	16	46
73	15	1.66	535	65	15	11	15	22
74	29	2.04	538	81	21	13	17	26
75	8	2.32	779	74	27	22	32	28
76	5	1.28	398	47	15	14	15	23
77	16	1.01	272	32	9	10	17	9
78	2	1.09	192	14	9	9	16	9
79	23	1.04	260	31	9	10	16	9
81	26	2.70	473	75	28	17	21	32
82	3	1.27	310	79	13	10	15	9
83	10	0.99	245	24	6	6	14	7
84	4	1.16	400	41	10	9	17	6
85	24	2.97	459	71	27	15	17	29
86	2	3.56	868	114	38	26	36	51
87	4	1.02	356	24	8	6	13	11
88	4	0.78	225	22	5	7	14	5
89	42	3.60	568	112	39	23	25	40
90	14	3.64	547	108	39	26	29	43
91	4	2.69	722	103	34	21	27	48
92	5	1.47	518	46	14	16	35	14
96	12	2.64	461	79	29	18	24	32
97	11	1.77	391	60	19	12	19	20
98	11	2.65	451	93	28	18	25	29
99	11	2.55	842	114	29	19	24	30
100	9	0.91	340	37	8	11	15	19
101	14	1.21	284	32	7	7	9	12
102	3	1.48	357	68	13	14	24	18
103	31	1.16	320	37	9	9	12	12
104	5	1.34	619	36	10	7	11	13
105	15	2.33	606	82	21	15	18	24
106	5	2.64	381	92	26	16	15	28
107	19	2.39	878	77	25	14	18	27
109	20	2.19	741	78	22	15	22	23
110	2	1.79	728	50	17	12	18	15
111	22	2.37	688	75	21	15	15	25
113	3	1.71	1142	58	11	13	19	34

Table 5. Summary of mean trace element contents data for soil landscape polygons - continued

SLC Polygon*	N	Fe %	Mn ppm	Zn ppm	Cu ppm	Co ppm	Pb ppm	Ni ppm
114	3	2.23	630	70	21	14	10	25
115	2	1.30	177	19	9	5	15	10
116	5	2.91	787	84	28	14	15	32
118	3	1.97	697	63	14	11	14	18
121	10	1.99	511	71	19	12	14	24
122	3	1.77	545	79	20	16	23	21
123	2	0.81	330	49	19	12	33	18
124	8	2.33	640	80	21	16	21	26
125	16	3.10	1264	137	35	18	16	44
126	18	2.38	528	80	24	16	18	28
127	6	0.99	455	45	10	12	18	15
129	3	2.14	1192	60	17	14	19	27
130	7	1.85	702	72	20	17	19	22
131	7	1.16	548	44	9	11	16	13
133	8	1.01	395	37	9	12	19	10
134	4	1.79	517	47	16	12	15	21
135	8	1.52	494	51	14	14	23	15
136	4	1.35	426	45	13	11	24	13
137	3	0.69	258	26	4	11	14	9
138	19	1.37	401	44	15	10	19	15
139	5	1.87	495	68	22	11	16	19
140	9	2.06	452	60	22	9	13	18
141	4	2.46	480	80	30	12	27	28
144	4	1.80	543	94	23	10	15	17
145	11	1.36	370	41	16	12	18	15
146	5	1.33	364	58	14	13	26	14
148	4	2.45	446	69	25	17	13	27
149	2	1.85	410	59	19	12	16	18
160	6	2.25	464	56	19	12	14	20
161	6	2.03	461	57	21	10	14	20
162	1	1.71	500	52	21	11	29	20
165	2	1.55	362	50	20	6	7	17
175	1	0.73	70	13	9	5	-	-
177	7	2.29	911	59	19	9	10	23
184	1	2.10	193	33	22	8	14	14
186	5	2.20	901	88	20	17	24	23
188	1	1.42	300	62	11	14	23	12
194	1	5.00	595	84	37	15	14	42
321	4	1.87	745	65	15	17	24	17
324	6	1.92	702	63	20	10	20	20
325	12	2.24	511	72	25	12	18	24
326	3	2.08	787	80	20	16	14	25
331	2	1.08	377	35	11	6	9	9
332	1	2.01	1575	92	25	23	14	34
333	5	1.55	576	51	16	11	14	17
337	1	2.10	466	64	24	12	8	23
407	4	2.20	299	40	17	9	16	18
411	1	2.20	232	92	28	9	13	22

Table 5. Summary of mean trace element contents data for soil landscape polygons - continued

SLC Polygon*	N	Ag ppm	Cd ppm	Hg ppb	Mo ppm	Se ppm	V ppm	N	As ppm	Cr ppm
3	1	0.2	0.1	70	2	0.8	78	-	-	-
4	1	0.1	0.1	120	2	0.7	65	-	-	-
5	2	0.3	0.1	70	5	0.5	71	-	-	-
6	5	0.2	0.1	50	3	0.3	27	-	-	-
7	3	0.2	0.2	50	2	0.2	31	-	-	-
8	1	0.2	0.1	40	4	0.6	76	-	-	-
9	10	0.2	0.2	76	3	0.4	87	2	8	46
11	3	0.2	0.3	37	4	0.5	100	2	6	43
13	1	0.2	0.1	20	3	0.1	36	1	5	30
14	2	0.1	0.2	30	3	0.1	82	1	8	64
17	6	0.1	0.1	18	2	0.2	50	6	4	30
18	2	0.2	0.1	15	3	0.4	78	2	6	42
19	1	0.1	0.1	30	3	0.1	37	-	-	-
20	3	0.1	0.1	60	3	0.5	34	2	3	30
22	4	0.2	0.1	68	2	0.5	90	3	7	52
24	1	0.1	0.2	20	1	0.3	33	-	-	-
26	2	0.2	0.1	65	4	0.5	76	-	-	-
29	3	0.2	0.2	93	4	0.4	99	-	-	-
30	6	0.2	0.2	75	3	0.4	55	-	-	-
31	6	0.2	0.3	87	3	0.8	94	1	5	26
32	3	0.1	0.2	33	2	0.3	60	2	4	19
33	8	0.2	0.2	58	3	0.3	44	1	6	34
34	2	0.1	0.2	15	2	0.2	36	2	3	24
35	2	0.1	0.2	20	2	0.1	40	2	4	26
36	2	0.2	0.1	80	5	0.5	75	-	-	-
37	4	0.2	0.2	78	3	0.6	70	-	-	-
38	2	0.2	0.2	65	2	0.6	80	-	-	-
40	4	0.1	0.2	50	3	0.4	82	2	6	46
42	2	0.1	0.2	25	3	0.4	70	2	6	41
43	2	0.2	0.2	90	3	0.6	94	-	-	-
44	9	0.2	0.1	35	3	0.3	73	8	5	42
45	2	0.3	0.1	40	3	0.3	104	-	-	-
46	5	0.2	0.1	64	2	0.4	40	-	-	-
47	4	0.2	0.1	43	3	0.5	82	3	6	48
49	3	0.2	0.1	77	3	0.6	80	-	-	-
50	3	0.2	0.1	63	3	0.5	61	-	-	-
53	9	0.2	0.2	70	3	0.4	81	-	-	-
55	7	0.2	0.1	67	2	0.3	50	1	7	51
56	12	0.1	0.1	46	2	0.2	39	3	4	21
57	3	0.1	0.1	33	2	0.2	36	2	4	19
58	19	0.2	0.1	32	2	0.3	55	16	6	33
59	19	0.1	0.2	44	2	0.3	71	10	6	35

Table 5. Summary of mean trace element contents data for soil landscape polygons - continued

SLC Polygon*	N	Ag ppm	Cd ppm	Hg ppb	Mo ppm	Se ppm	V ppm	N	As ppm	Cr ppm
61	1	0.3	0.3	120	4	0.8	91	-	-	-
62	2	0.1	0.2	20	3	0.4	71	-	-	-
63	14	0.2	0.3	48	4	0.6	105	10	8	51
64	4	0.2	1.8	105	4	1.6	201	2	13	104
65	1	0.2	0.3	50	2	0.5	60	-	-	-
66	25	0.2	0.1	85	3	0.4	95	-	-	-
67	10	0.2	0.2	82	4	0.6	119	1	6	38
68	24	0.2	0.2	81	3	0.5	103	-	-	-
69	2	0.2	0.1	80	4	0.3	105	1	7	44
70	4	0.2	0.2	45	4	0.4	129	3	7	67
71	3	0.2	0.2	100	4	0.3	159	-	-	-
72	15	0.3	2.2	67	5	1.1	201	9	12	81
73	7	0.1	0.6	39	3	0.6	120	5	9	63
74	17	0.2	0.4	71	4	0.4	112	5	6	61
76	4	0.2	0.2	125	2	0.4	76	-	-	-
77	8	0.2	0.1	74	3	0.3	35	1	1	24
78	1	0.2	0.1	10	1	0.1	31	1	1	24
79	7	0.2	0.1	41	2	0.2	36	5	1	28
81	11	0.2	0.1	62	3	0.5	91	2	5	75
82	1	0.1	0.1	50	4	0.6	63	-	-	-
83	7	0.1	0.1	47	1	0.2	25	-	-	-
84	2	0.2	0.1	65	2	0.3	34	-	-	-
85	17	0.2	0.1	34	2	0.3	103	17	5	75
86	1	0.1	0.1	120	5	0.7	116	-	-	-
87	2	0.2	0.1	20	2	0.2	28	2	1	20
88	2	0.2	0.1	115	1	0.1	20	-	-	-
89	21	0.2	0.1	69	4	0.4	143	-	-	-
90	3	0.1	0.2	53	3	0.3	131	-	-	-
91	2	0.3	0.1	100	5	0.4	104	-	-	-
96	6	0.2	0.1	57	4	0.5	95	-	-	-
97	4	0.2	0.1	40	4	0.4	82	-	-	-
98	4	0.1	0.1	80	3	0.4	97	-	-	-
100	1	0.3	0.1	50	4	0.6	39	-	-	-
101	11	0.2	0.2	23	1	0.2	39	3	6	47
103	14	0.2	0.1	39	3	0.2	46	6	6	37
104	4	0.2	0.2	95	4	0.3	36	-	-	-
105	6	0.2	0.2	55	4	0.5	89	4	11	61
106	4	0.2	0.1	83	5	1.2	80	1	5	66
107	9	0.2	0.2	88	4	0.4	97	3	7	48
109	3	0.1	0.2	70	3	0.4	95	-	-	-

Table 5. Summary of mean trace element contents data for soil landscape polygons - continued

SLC Polygon*	N	Ag ppm	Cd ppm	Hg ppb	Mo ppm	Se ppm	V ppm	N	As ppm	Cr ppm
111	9	0.2	0.1	37	3	0.4	107	7	7	58
114	3	0.2	0.1	100	4	0.3	81	-	-	-
115	2	0.2	0.2	15	3	0.1	31	2	1	33
116	4	0.2	0.2	53	4	0.4	132	2	12	70
118	2	0.3	0.4	60	2	0.7	64	-	-	-
121	5	0.3	0.1	60	4	0.6	70	-	-	-
124	4	0.1	0.4	63	3	1.3	83	2	5	47
125	12	0.2	0.3	75	6	0.9	156	10	13	76
126	11	0.2	0.2	67	10	1.3	97	6	15	53
127	2	0.1	0.1	75	1	0.6	29	-	-	-
129	1	0.2	0.1	70	2	1.8	83	-	-	-
130	1	0.2	0.1	10	2	0.5	42	-	-	-
131	2	0.2	0.1	90	4	0.6	47	-	-	-
134	2	0.3	0.1	55	4	0.2	50	1	4	60
135	2	0.2	0.2	40	3	1.1	53	-	-	-
138	7	0.2	0.1	56	3	0.6	51	1	8	49
139	3	0.1	0.2	137	3	0.8	62	-	-	-
140	7	0.3	0.1	80	3	0.6	65	2	3	78
141	1	0.2	0.2	110	3	0.4	73	-	-	-
144	3	0.2	0.2	60	3	0.8	51	-	-	-
145	7	0.1	0.1	41	4	0.4	47	-	-	-
146	2	0.3	0.1	25	4	0.3	30	-	-	-
148	4	0.2	0.1	95	4	0.6	77	-	-	-
149	2	0.2	0.2	70	4	0.6	55	-	-	-
160	6	0.2	0.1	63	3	0.4	66	1	7	110
161	4	0.2	0.1	68	3	0.4	60	1	3	65
162	1	0.2	-	-	-	-	-	-	-	-
165	2	0.2	0.1	65	3	0.8	45	1	2	40
177	7	0.2	0.2	37	3	0.2	90	7	8	47
184	1	0.1	0.1	20	3	0.4	41	1	3	36
186	2	0.2	0.6	75	3	0.9	72	-	-	-
188	1	0.2	-	-	-	-	-	-	-	-
194	1	0.2	0.1	40	3	0.1	120	1	7	85
321	1	0.2	0.1	40	2	0.6	80	-	-	-
324	4	0.3	0.1	63	4	0.3	77	-	-	-
325	9	0.2	0.1	84	4	0.5	87	-	-	-
326	2	0.3	0.3	80	5	0.6	78	-	-	-
331	2	0.2	0.1	35	3	0.1	29	-	-	-
333	3	0.2	0.1	100	4	0.3	50	-	-	-
337	1	0.2	0.1	30	3	0.5	69	-	-	-
407	4	0.2	0.1	25	3	0.1	65	4	3	47
411	1	0.1	0.2	20	3	0.2	50	1	5	59

*Soil landscape polygons from the 1:1 million scale Soil Landscapes of Canada-Manitoba Map (Canada Soil Inventory, 1989).

Table 6. Summary of mean trace element content by soil series

Soil Series	Soil Code	N	Ag ppm	Cd ppm	Hg ppb	Mo ppm	Se ppm	V ppm	N	As ppm	Cr ppm
Arborg	ABG	1	0.2	0.1	90	3	0.6	128	--	--	--
Ashdown	AHW	2	0.2	0.2	15	2	0.2	38	2	3	24
Aneda	AND	1	0.2	0.1	70	4	0.6	55	--	--	--
Angusville	ANL	3	0.2	0.1	50	3	0.2	82	1	7	47
Alonsa	AOS	1	0.3	0.3	60	3	1.0	56	--	--	--
Assiniboine	ASB	1	0.3	0.1	70	3	0.3	105	--	--	--
Almasippi	ASS	5	0.2	0.1	44	3	0.3	40	--	--	--
Altamont	ATN	4	0.2	0.2	85	3	0.5	92	1	6	38
Arrow Hills	AWH	1	0.2	0.1	30	3	1.3	207	1	9	76
Balmoral	BAM	2	0.2	0.2	120	4	0.7	47	--	--	--
Blackstone	BCS	1	0.4	0.4	50	4	0.9	155	--	--	--
Bede	BED	2	0.1	0.1	15	2	0.2	36	2	3	24
Bearford	BEF	1	0.1	0.2	30	3	0.3	81	1	6	48
Benton	BEO	1	0.2	0.3	150	5	3.0	128	--	--	--
Berlo	BLO	1	0.2	0.1	110	2	0.3	34	--	--	--
Blumengart	BMG	5	0.5	3.3	70	7	1.6	307	4	18	119
Beresford	BSF	10	0.2	0.2	79	4	0.7	78	1	5	26
Blumenort	BUM	3	0.2	1.9	63	5	1.1	180	2	11	74
Barwood	BWO	2	0.2	0.1	23	4	0.5	64	2	4	43
Cobfield	CBF	3	0.2	0.1	47	3	0.5	88	2	4	41
Chambers	CBS	1	0.3	0.3	80	4	0.3	71	--	--	--
Colby	CBY	1	0.1	0.1	160	2	0.3	35	--	--	--
Chesterfield	CHF	2	0.2	0.2	30	3	0.4	71	2	5	41
Caliento	CIO	1	0.1	0.2	10	2	0.1	29	1	1	27
Clarkleigh	CKG	9	0.2	0.1	90	4	1.0	70	1	5	66
Cameron	CMR	1	0.2	0.1	70	4	0.5	72	--	--	--
Coatstone	CSE	1	0.1	0.1	80	2	0.6	76	--	--	--
Cordova	CVA	5	0.2	0.2	76	3	0.6	87	1	7	53
Carroll	CXF	5	0.2	0.1	90	4	0.3	80	--	--	--
Capell	CXT	1	0.2	0.2	90	4	0.5	53	--	--	--
Charman	CXV	2	0.2	0.1	70	4	0.7	88	--	--	--
Croyon	CYN	9	0.1	0.1	65	3	0.3	65	2	5	29
Denbow	DBW	1	0.2	0.1	60	4	0.4	32	--	--	--
Dencross	DCS	4	0.2	0.1	30	3	0.3	92	2	4	55
Darlingford	DGF	8	0.3	0.1	84	4	0.7	124	--	--	--
Deadhorse	DHO	1	0.4	7.9	130	8	1.7	455	--	--	--
Duck Mountain	DKM	1	0.1	0.2	30	4	0.2	82	1	6	48
Daly	DLY	6	0.2	0.4	72	4	1.1	126	4	7	54
Denham	DNH	1	0.2	0.8	108	6	0.7	135	--	--	--
Dorset	DOT	7	0.2	0.1	49	2	0.3	31	1	5	28
Dauphin	DPH	7	0.2	0.3	67	5	0.6	161	6	13	79
Durban	DRB	2	0.2	0.5	75	3	0.9	72	--	--	--
Dromore	DRO	2	0.2	0.2	130	5	0.5	102	--	--	--
Dutton	DTT	1	0.2	0.2	110	5	2.1	112	--	--	--
Dezwood	DZW	15	0.2	0.3	79	4	0.5	105	2	11	51
Erickson	ECK	6	0.2	0.2	62	3	0.3	84	4	9	49
Edwards	EWS	1	0.1	0.8	100	11	2.0	152	1	24	70

Table 6. Summary of mean trace element content by soil series - continued

Soil Series	Soil Code	N	Ag ppm	Cd ppm	Hg ppb	Mo ppm	Se ppm	V ppm	N	As ppm	Cr ppm
Fairford	FFD	1	0.1	0.1	30	3	0.1	58	1	3	65
Firdale	FIR	1	0.3	0.3	120	4	0.8	91	--	--	--
Framnes	FMS	2	0.2	0.1	40	1	0.5	120	2	6	88
Fairland	FND	2	0.2	0.1	30	2	0.3	70	2	8	40
Foley	FOY	1	0.3	0.1	60	1	0.3	39	--	--	--
Fyala	FYL	7	0.2	0.2	53	3	0.5	114	4	8	110
Glenboro	GBO	4	0.2	0.1	58	3	0.4	57	2	6	31
Gilbert	GBT	1	0.2	0.1	90	5	0.4	42	--	--	--
Gnadenthal	GDH	4	0.1	0.2	32	4	0.2	72	4	7	41
Glenfields	GFS	4	0.2	0.2	48	2	0.5	77	2	3	50
Glenhope	GHP	2	0.2	0.2	20	2	0.7	45	--	--	--
Glenmoor	GOO	14	0.2	0.1	48	3	0.4	96	7	6	78
Gretna	GRA	4	0.1	1.2	55	4	0.9	154	3	7	64
Grover	GRO	1	0.2	0.1	90	2	0.2	47	--	--	--
Guerra	GRR	2	0.1	1.4	35	4	0.9	143	2	11	60
Graysville	GYV	1	0.1	0.2	60	4	0.3	110	1	20	70
Hallboro	HAL	1	0.1	0.1	40	2	0.4	60	--	--	--
Halicz	HCZ	2	0.2	0.1	30	4	1.2	63	2	5	47
Hoddinott	HDN	1	0.4	0.1	120	5	0.5	123	--	--	--
Hochfeld	HHF	2	0.2	0.2	105	4	0.3	59	--	--	--
Hathaway	HHY	5	0.2	0.1	70	3	0.7	74	--	--	--
Hilton	HIT	7	0.2	0.1	36	3	0.4	71	4	6	43
Homestead	HMD	1	0.4	0.8	60	2	1.1	88	--	--	--
Horndean	HND	2	0.2	0.5	30	3	0.4	110	2	7	52
Horose	HOS	2	0.2	0.6	40	4	1.2	81	2	5	47
Horton	HOT	3	0.1	0.2	50	3	0.4	82	2	6	46
Horod	HRD	1	0.2	0.2	20	2	0.1	50	1	4	27
Harding	HRG	4	0.2	0.1	65	4	0.3	127	2	10	63
Isafold	ISF	7	0.2	0.2	77	2	0.6	50	--	--	--
Inwood	IWO	10	0.2	0.1	48	3	0.3	45	2	2	34
Jaymar	JAY	2	0.2	0.2	115	5	0.4	69	--	--	--
Joyale	JYL	10	0.2	0.2	88	3	0.5	97	--	--	--
Keld	KLD	2	0.3	0.1	60	29	3.7	135	2	27	73
Kerr Lake	KRL	1	0.3	0.1	40	2	0.2	164	1	8	67
Knudson	KUD	12	0.2	0.1	73	3	0.4	98	2	7	51
Kilmury	KUY	1	0.3	0.1	110	1	0.3	44	--	--	--
Libau	LBU	1	0.5	0.3	60	3	0.5	105	--	--	--
Levine	LEI	3	0.2	0.2	40	3	0.7	92	3	6	51
Lakeland	LKD	6	0.2	0.1	48	4	0.4	79	3	3	44
Lockhart	LKH	1	0.1	0.1	30	4	0.1	74	1	6	42
Lelant	LLT	6	0.2	0.2	70	3	0.3	35	--	--	--
Long Plain	LOP	4	0.2	0.2	20	2	0.1	32	2	3	26
Leary	LRY	4	0.2	0.1	30	2	0.2	30	3	3	25
Lonesand	LSD	4	0.1	0.1	10	2	0.1	32	1	1	26
Lenswood	LSW	4	0.1	0.1	48	2	0.5	34	2	3	22
Lauder	LUD	1	0.1	0.1	130	4	0.4	40	--	--	--
Lundar	LUR	17	0.2	0.1	72	3	0.6	52	--	--	--

Table 6. Summary of mean trace element content by soil series - continued

Soil Series	Soil Code	N	Ag ppm	Cd ppm	Hg ppb	Mo ppm	Se ppm	V ppm	N	As ppm	Cr ppm
Lyleton	LYT	2	0.1	0.2	20	2	0.1	40	2	4	26
Ladywood	LYW	2	0.1	0.1	35	3	0.3	40	--	--	--
Marsden	MDN	1	0.2	0.1	40	3	0.1	97	1	8	54
Meleb	MEB	1	0.1	0.1	40	5	0.7	73	--	--	--
Meharry	MEH	3	0.1	0.1	47	10	0.9	97	2	14	64
Mowbray	MOW	2	0.2	0.1	90	4	0.4	101	--	--	--
Marringhurst	MRH	5	0.2	0.2	40	2	0.3	33	2	3	20
Marquette	MRQ	10	0.2	0.1	88	4	0.5	98	--	--	--
Meadowbrook	MWK	1	0.1	0.3	50	8	0.5	194	1	12	84
Miniota	MXI	1	0.1	0.2	30	2	0.3	48	1	6	32
Manitou	MXS	12	0.2	0.1	80	3	0.4	106	--	--	--
Melland	MXT	2	0.2	0.1	65	4	0.4	52	--	--	--
Neuenberg	NBG	3	0.2	0.1	27	3	0.2	50	1	4	27
Newdale	NDL	14	0.2	0.2	74	3	0.4	91	1	8	58
Nanton	NTO	1	0.2	0.6	100	2	0.6	127	--	--	--
Neuhorst	NUH	1	0.2	0.1	70	4	0.5	82	1	9	70
Newton Siding	NWN	1	0.2	0.1	40	3	0.2	77	1	6	47
Osborne	OBO	20	0.2	0.1	75	4	0.4	141	--	--	--
Oaknook	ONK	2	0.3	0.2	120	5	0.5	97	--	--	--
Ophir	OPH	2	0.2	0.1	15	3	0.1	31	2	0.7	33
Prodan	PDA	3	0.2	0.2	43	3	0.5	85	2	8	51
Penrith	PEN	1	0.1	0.2	40	2	0.1	92	1	6	64
Peguis	PGU	3	0.1	0.1	60	3	0.4	93	2	3	78
Pleasant	PLE	1	0.4	0.2	90	2	0.3	47	--	--	--
Pelan	PLN	2	0.3	0.1	85	4	0.4	37	--	--	--
Plum Coulee	PME	6	0.2	0.7	50	3	0.8	162	4	10	81
Plum Ridge	PMG	3	0.2	0.1	60	3	0.3	56	1	5	34
Poppleton	PPL	5	0.2	0.1	50	2	0.2	34	1	1	24
Petlura	PTU	3	0.1	0.2	50	4	0.3	97	1	12	55
Paulson	PUO	1	0.2	0.1	70	12	0.8	160	1	12	86
Plainview	PVW	2	0.3	0.1	80	2	1.3	101	--	--	--
Ramada	RAM	11	0.1	0.1	57	2	0.4	79	5	6	42
Roblin	RBN	5	0.1	0.1	82	4	0.4	88	1	8	45
Rennie River	REN	1	0.1	0.1	20	2	0.1	38	1	0.3	18
Reinfeld	RFD	1	0.1	0.4	70	4	0.4	76	--	--	--
Rignold	RGD	2	0.2	0.1	60	4	0.4	71	1	5	44
Regent	RGT	1	0.1	0.3	50	4	0.3	79	--	--	--
Red River	RIV	18	0.2	0.2	63	3	0.4	135	4	6	76
Rackham	RKH	1	0.2	0.3	50	3	0.3	81	1	8	44
Reinland	RLD	2	0.2	0.1	25	3	0.4	47	--	--	--
Rufford	RUF	5	0.1	0.2	62	3	0.4	95	--	--	--
Ryerson	RYS	2	0.1	0.2	65	4	0.8	76	--	--	--
Stockton	SCK	11	0.1	0.1	60	2	0.2	42	4	4	27
Scanterbury	SCY	2	0.3	0.2	65	4	0.4	148	--	--	--
Sandilands	SDI	10	0.1	0.1	58	2	0.2	24	--	--	--
Sigmund	SGO	1	0.2	0.4	70	4	0.6	142	--	--	--
Seech	SHH	1	0.2	0.2	20	3	0.1	49	1	4	31

Table 6. Summary of mean trace element content by soil series - continued

Soil Series	Soil Code	N	Ag ppm	Cd ppm	Hg ppb	Mo ppm	Se ppm	V ppm	N	As ppm	Cr ppm
Shilox	SHX	8	0.2	0.1	26	3	0.1	35	3	4	21
Sirko	SIK	1	0.1	0.1	50	4	0.1	32	--	--	--
Skelding	SKL	4	0.1	0.1	21	2	0.2	24	--	--	--
St. Labre	SLB	1	0.1	0.1	10	3	0.1	37	1	2	35
Selina	SLN	1	0.1	0.1	90	4	0.2	31	--	--	--
Souris	SOU	6	0.1	0.1	20	2	0.3	36	4	3	23
Sprague	SPG	3	0.2	0.1	23	3	0.2	31	1	0.7	24
Swanford	SWF	2	0.2	0.1	50	2	0.6	47	--	--	--
Switzer	SWZ	2	0.1	0.2	40	3	0.2	31	--	--	--
Tadpole	TDP	2	0.3	0.2	35	6	0.7	115	2	9	54
Telford	TFD	2	0.2	0.1	15	3	0.3	34	2	2	28
Tiger Hills	TGL	2	0.2	0.1	65	2	0.3	61	--	--	--
Taggart	TGR	1	0.2	0.2	60	2	0.6	76	--	--	--
Thalberg	THG	3	0.1	0.1	40	3	0.3	113	3	6	88
Torcan	TOC	1	0.1	0.2	70	2	0.3	63	--	--	--
Two Creeks	TWC	2	0.2	0.1	65	4	0.5	76	--	--	--
Ullrich	ULH	4	0.1	0.2	45	3	0.5	93	2	6	56
Vita	VIT	1	0.2	0.1	150	2	0.3	44	--	--	--
Valley	VLY	1	0.2	0.2	40	2	0.1	118	1	12	54
Varcoe	VRC	8	0.2	0.1	68	4	0.3	70	1	8	63
Wintergreen	WGE	1	0.2	0.1	10	2	0.1	27	1	0.9	22
Wheatland	WHL	11	0.1	0.1	31	2	0.3	38	7	5	21
Winkler	WIK	2	0.2	0.2	70	5	0.4	115	--	--	--
Waskada	WKD	6	0.2	0.2	43	3	0.4	75	4	6	45
Wampum	WMP	1	0.4	0.2	10	2	0.5	27	--	--	--
Woodridge	WOG	5	0.2	0.1	58	2	0.2	30	1	5	30
Woodmore	WOM	1	0.1	0.1	110	2	0.5	43	--	--	--
Waitville	WTV	2	0.3	0.3	35	4	0.3	62	2	6	36
Wolverton	WVT	1	0.1	0.2	20	3	0.2	50	1	5	59
Willowbend	WWB	1	0.1	0.2	40	4	0.3	80	1	12	53
Willowcrest	WWC	3	0.2	0.1	47	2	0.2	29	1	3	28
Wellwood	WWD	7	0.2	0.2	59	3	0.4	74	2	6	35
Zinman	ZIM	2	0.2	0.3	80	3	0.4	103	--	--	--

Table 6. Summary of mean trace element content by soil series - continued

Soil Series	Soil Code	N	Fe %	Mn ppm	Zn ppm	Cu ppm	Co ppm	Pb ppm	Ni ppm
Arborg	ABG	1	3.50	650	103	41	23	15	46
Ashdown	AHW	2	1.45	1472	31	8	6	10	14
Aneda	AND	2	1.79	399	49	19	9	9	14
Angusville	ANL	4	2.13	693	61	20	12	11	22
Alonsa	AOS	1	2.10	800	173	31	10	14	15
Arden	ARD	1	1.96	502	78	23	15	17	56
Assiniboine	ASB	5	2.76	1049	108	24	26	24	30
Almasippi	ASS	16	0.97	312	38	8	9	13	15
Agassiz	ASZ	1	0.73	277	17	4	5	4	6
Altamont	ATN	7	1.94	1119	82	19	15	14	25
Arrow Hills	AWH	3	2.25	622	83	16	17	13	20
Balmoral	BAM	4	2.26	507	71	23	18	22	23
Blackstone	BCS	1	3.00	1020	138	27	23	21	32
Bede	BED	5	1.12	373	28	5	10	13	10
Bearford	BEF	1	2.60	561	66	22	9	10	24
Benton	BEO	1	2.60	4560	110	26	22	20	69
Bernice	BIC	1	1.80	682	56	13	17	22	15
Berlo	BLO	1	0.90	336	39	11	7	15	9
Blumengart	BMG	5	3.28	1274	164	43	15	14	60
Bermont	BMN	1	2.20	900	72	16	21	24	22
Broomhill	BOH	1	1.74	814	59	9	16	21	12
Bower	BOW	1	1.74	868	74	20	18	19	19
Beresford	BSF	12	2.34	686	89	23	13	12	25
Blumenort	BUM	3	2.87	2083	134	39	12	17	56
Beaverdam Lake	BVR	2	0.92	304	25	8	12	22	11
Barwood	BWO	5	2.02	682	65	16	13	15	20
Berry Island	BYD	3	0.88	325	43	13	10	18	11
Cobfield	CBF	3	2.13	987	85	18	10	13	23
Chambers	CBS	1	2.40	630	54	18	10	6	20
Colby	CBY	3	0.95	304	32	9	10	14	9
Chesterfield	CHF	2	1.95	411	51	14	9	9	18
Caliento	CIO	2	1.20	279	20	9	7	16	9
Crookdale	CKD	1	1.85	731	64	15	18	17	18
Clarkleigh	CKG	14	2.03	420	71	23	12	18	21
Clementi	CLN	2	2.62	916	90	23	25	23	27
Cranmer	CME	2	1.89	855	81	18	19	25	25
Cameron	CMR	2	1.89	679	73	18	18	18	20
Coatstone	CSE	4	1.92	799	70	15	18	22	19
Cordova	CVA	15	2.08	764	71	22	14	22	23
Carroll	CXF	6	2.13	899	85	19	18	22	24
Capell	CXT	2	1.79	1572	71	16	12	14	16
Charman	CXV	2	2.45	643	79	20	10	11	23
Croyon	CYN	10	1.89	795	63	14	8	10	16
Denbow	DBW	1	0.90	390	34	5	10	11	11
Dencross	DCS	11	2.72	628	75	28	18	23	33
Darlingford	DGF	11	2.26	1066	104	29	13	15	31
Deadhorse	DHO	6	2.60	905	150	39	18	24	41
Duck Mountain	DKM	1	2.50	1050	51	21	10	9	30
Daly	DLY	6	2.92	857	103	29	14	14	34
Denham	DNH	4	2.35	742	98	30	14	12	33
Dromore	DOM	1	1.78	991	69	12	15	19	15

Table 6. Summary of mean trace element content by soil series - continued

Soil Series	Soil Code	N	Fe %	Mn ppm	Zn ppm	Cu ppm	Co ppm	Pb ppm	Ni ppm
Dorset	DOT	11	1.27	612	43	9	7	14	11
Dauphin	DPH	9	3.12	1186	140	33	17	17	43
Durban	DRB	2	1.75	870	73	15	13	15	20
Drokan	DRO	2	2.35	829	77	25	13	10	30
Dutton	DTT	2	2.08	620	88	25	15	18	28
Druxman	DXM	1	1.54	1304	45	9	12	16	13
Dezwood	DZW	20	2.19	1230	92	19	12	13	26
Erickson	ECK	13	2.26	886	73	21	16	17	25
Elm Creek	EEK	1	1.81	485	60	18	11	19	16
Elva	ELV	1	2.01	710	84	16	21	23	21
Elm River	EMV	1	1.77	589	79	16	19	20	35
Edwards	EWS	2	3.16	1664	124	32	18	19	39
Eddystone	EYT	1	1.16	290	35	11	6	14	14
Fairford	FFD	1	2.50	340	43	23	9	10	28
Firdale	FIR	2	1.79	600	61	20	13	16	19
Framnes	FMS	2	3.45	618	92	29	14	16	33
Fairland	FND	5	1.89	561	68	15	14	16	18
Foley	FOY	2	1.25	325	28	12	8	13	12
Fortier	FTE	2	2.68	772	102	26	24	23	32
Fyala	FYL	9	3.35	473	84	31	18	22	37
Glenboro	GBO	4	1.73	506	56	14	10	11	16
Gilbert	GBT	2	1.22	607	46	8	10	8	13
Glencross	GCS	2	1.94	599	85	25	18	25	36
Grande Clairiere	GDC	1	0.80	346	27	3	13	10	8
Gnadenthal	GDH	9	2.01	562	84	19	12	16	18
Glenfields	GFS	7	2.26	526	60	26	15	20	25
Grifton	GFT	1	2.25	1020	41	11	13	---	---
Glenhope	GHP	11	1.22	389	43	13	12	20	12
Goose Island	GOI	1	0.73	70	13	9	5	---	---
Goodlands	GOL	1	1.84	708	71	15	20	22	25
Glenmoor	GOO	15	3.01	504	77	29	13	14	29
Gretna	GRA	4	2.68	1599	114	31	12	15	47
Garrioch	GRH	1	1.14	335	---	30	16	33	12
Grover	GRO	1	1.50	507	42	13	9	10	13
Guerra	GRR	3	2.43	1318	93	26	13	13	43
Garson	GSO	1	2.46	540	73	19	22	30	23
Gunton	GUO	1	1.29	627	32	5	15	25	10
Gervais	GVS	1	1.60	614	80	15	16	---	---
Graysville	GYV	2	3.38	636	123	27	19	13	39
Hallboro	HAL	1	1.50	504	60	14	7	11	14
Halstead	HAT	1	1.54	510	51	13	16	18	14
Halicz	HCZ	3	2.52	557	72	18	13	11	26
Hoddinott	HDN	1	3.00	824	114	40	17	15	34
Hebbot	HEB	1	2.02	1810	82	17	19	17	25
Hochfeld	HHF	3	1.44	424	49	10	10	14	15
Hathaway	HHY	15	1.87	765	65	16	17	20	21
Hilton	HIT	15	2.01	783	60	16	14	16	20
Homestead	HMD	1	2.50	1250	110	25	17	23	31
Horndean	HND	4	2.35	860	97	25	16	19	32
Horose	HOS	2	2.25	741	75	19	7	10	26
Horton	HOT	4	2.17	584	57	17	15	15	20

Table 6. Summary of mean trace element content by soil series - continued

Soil Series	Soil Code	N	Fe %	Mn ppm	Zn ppm	Cu ppm	Co ppm	Pb ppm	Ni ppm
Horod	HRD	1	1.30	567	71	9	6	6	13
Harding	HRG	4	3.30	673	103	28	15	14	33
Hartney	HRY	1	1.32	583	47	9	11	16	11
Isafold	ISF	7	1.77	504	60	19	9	10	15
Inwood	IWO	16	1.57	396	44	15	11	16	16
Jaymar	JAY	2	2.05	565	60	21	10	6	23
Joyale	JYL	14	2.04	1050	79	19	12	13	23
Kingsley	KIS	1	2.00	1537	71	14	19	19	20
Keld	KLD	2	2.70	32	44	31	7	18	12
Kline	KLI	1	1.42	250	47	23	9	22	5
Kerr Lake	KRL	1	2.80	940	74	12	10	11	24
Kergwenan	KRW	1	0.70	213	21	3	11	15	6
Knudson	KUD	13	2.15	1166	80	21	11	12	26
Kilmury	KUY	1	1.50	663	55	13	13	15	16
Lambert	LAM	1	0.85	325	42	11	13	25	10
Libau	LBU	2	3.43	565	95	39	22	25	40
Levine	LEI	3	2.63	746	80	18	10	11	23
Langvale	LGV	1	0.83	425	28	8	14	10	12
Lakeland	LKD	19	1.84	537	60	20	15	25	20
Lockhart	LKH	1	2.70	458	53	21	9	8	24
Lelant	LLT	7	1.24	502	31	10	6	8	12
Lenore	LNO	1	1.57	977	55	9	20	10	18
Long Plain	LOP	8	0.99	239	25	5	7	10	13
Leary	LRY	6	1.47	1196	35	10	8	14	10
Lonesand	LSD	1	1.00	162	21	6	4	9	8
Lenswood	LSW	16	0.97	423	38	8	11	16	12
Lauder	LUD	5	0.87	333	31	6	12	11	8
Lundar	LUR	33	1.63	448	53	18	10	18	16
Lyleton	LYT	5	1.43	431	41	8	11	15	9
Ladywood	LYW	2	1.15	324	31	13	9	9	12
McCreary	MCR	7	1.71	469	58	19	15	29	21
Marsden	MDN	1	2.70	644	68	21	9	12	29
Meleb	MEB	2	2.21	400	112	22	17	27	23
Meharry	MEH	8	2.32	515	76	22	17	20	28
Magnet	MGT	1	1.02	405	46	13	16	17	18
Methley	MHY	3	1.97	560	66	21	18	42	21
Mckinley	MLI	1	1.03	110	74	21	10	15	11
McClernon	MND	1	2.13	440	110	22	30	25	41
Malonton	MNT	3	0.88	267	33	8	13	24	10
Montgomery	MOT	2	1.84	590	71	17	17	25	18
Mowbray	MOW	3	1.95	1262	84	18	14	11	24
Maples	MPS	1	1.69	951	68	12	16	21	13
Margaret	MRE	1	1.37	555	49	9	14	15	10
Marringhurst	MRH	13	1.41	594	45	9	10	17	16
Marquette	MRQ	25	2.79	521	92	30	19	26	30
Morris	MRS	1	3.64	568	118	39	30	33	36
Meadowbrook	MWK	2	3.16	866	97	27	18	24	31
Miniota	MXI	9	1.59	925	55	11	13	16	21
Manitou	MXS	16	2.13	1031	89	22	13	14	25
Melland	MXT	3	1.75	786	66	18	12	15	19
Neuenberg	NBG	7	1.38	438	53	12	11	16	15

Table 6. Summary of mean trace element content by soil series - continued

Soil Series	Soil Code	N	Fe %	Mn ppm	Zn ppm	Cu ppm	Co ppm	Pb ppm	Ni ppm
Newdale	NDL	54	2.19	827	78	23	15	20	24
Neelin	NEI	1	1.93	1509	85	15	18	21	20
Norgate	NGT	1	2.97	759	137	22	20	25	37
Niverville	NIV	1	1.64	442	---	27	17	36	20
Nikkel	NKK	1	1.61	---	137	19	15	19	28
Napinka	NPK	1	0.95	484	39	6	11	22	8
Nanton	NTO	1	2.90	1210	108	35	12	15	35
Neuhorst	NUH	5	2.75	834	96	27	19	26	35
Newton Siding	NWN	1	2.30	466	54	21	8	10	21
Newstead	NWS	3	1.55	659	61	13	16	17	14
Osborne	OBO	47	3.64	567	107	38	24	26	41
Ochre River	OHV	2	3.18	1589	152	36	28	28	56
Oliver	OIV	1	2.11	1606	105	20	22	16	27
Oaknook	ONK	2	2.35	398	62	28	11	7	31
Ophir	OPH	2	1.30	177	19	9	5	15	10
Pansy	PAN	1	0.78	195	--	6	12	19	10
Pembina	PBI	1	1.93	1625	66	15	19	20	25
Prodan	PDA	5	2.40	744	91	19	14	15	23
Penrith	PEN	1	2.90	606	54	18	10	10	29
Peguis	PGU	8	3.04	491	80	29	22	24	43
Piney	PIY	3	1.33	293	66	11	13	25	11
Pleasant	PLE	1	1.40	556	40	11	12	13	12
Pelan	PLN	7	1.21	327	37	12	13	19	17
Plum Coulee	PME	6	2.80	930	107	32	12	14	40
Plum Ridge	PMG	15	1.39	410	48	13	12	20	14
Porple	POR	1	2.09	1003	81	16	19	20	24
Poppleton	PPL	10	1.04	270	26	7	8	14	8
Pine Ridge	PRG	2	1.16	276	29	3	11	15	6
Petlura	PTU	3	2.53	643	67	23	11	8	27
Paulson	PUO	1	3.80	1300	127	46	12	17	44
Plumas	PUS	1	0.97	398	32	9	12	22	9
Plainview	PVW	4	2.78	1049	123	29	24	22	41
Powell	PWL	1	1.32	930	50	15	14	---	---
Ramada	RAM	17	2.13	783	86	20	15	15	24
Rosebank	RBK	1	1.04	262	35	7	10	---	---
Roblin	RBN	5	2.50	721	62	22	11	11	25
Rose Ridge	RDG	1	3.08	836	78	25	26	27	31
Rennie River	REN	1	1.60	165	23	8	5	19	6
Reinfeld	RFD	3	1.70	547	87	14	12	14	17
Rignold	RGD	6	1.96	473	92	19	16	19	22
Regent	RGT	1	2.10	798	65	22	17	17	24
Red River	RIV	38	3.37	560	107	37	22	24	39
Rackham	RKH	1	2.20	1610	60	19	10	11	28
Reinland	RLD	10	1.07	372	39	10	11	16	14
Ralston	RTO	1	0.83	275	25	3	12	14	7
Rufford	RUF	12	2.03	743	69	19	15	17	23
Rathwell	RWL	1	2.49	775	153	26	18	25	30
Ryerson	RYS	2	2.05	810	74	18	16	15	21
Scarth	SCH	2	1.21	329	39	7	12	21	11
Stockton	SCK	15	1.20	378	36	8	8	12	11
Sclater	SCL	1	2.90	345	37	12	19	---	---

Table 6. Summary of mean trace element content by soil series - continued

Soil Series	Soil Code	N	Fe %	Mn ppm	Zn ppm	Cu ppm	Co ppm	Pb ppm	Ni ppm
Scanterbury	SCY	2	3.45	594	111	37	14	12	36
Sandilands	SDI	14	0.80	240	22	6	5	11	7
Sigmund	SGO	1	3.00	774	124	38	17	17	40
Seech	SHH	1	1.60	695	34	9	6	7	14
Shilox	SHX	14	1.27	386	31	7	8	11	13
Sirko	SIK	1	1.40	560	49	13	6	10	13
Skelding	SKL	6	0.82	230	26	4	6	9	7
St. Labre	SLB	4	0.95	221	22	5	7	19	9
Selina	SLN	1	0.75	290	24	8	8	13	5
Souris	SOU	13	1.06	377	30	6	9	13	9
Sprague	SPG	4	1.06	246	24	10	7	6	7
Stanton	STU	5	1.06	395	36	5	12	15	10
St. Claude	SUE	4	0.88	287	46	9	10	29	9
Swanford	SWF	3	1.47	635	55	14	12	18	16
Switzer	SWZ	3	1.06	467	39	8	8	10	11
Traverse	TAV	1	1.74	767	75	17	17	28	16
Tadpole	TDP	2	3.00	707	86	22	10	12	27
Telford	TFD	2	1.65	168	26	15	6	17	10
Tiger Hills	TGL	4	1.74	876	48	14	15	14	22
Taggart	TGR	1	1.80	669	57	15	18	20	20
Thalberg	THG	6	3.07	547	75	30	17	21	30
Torcan	TOC	2	1.72	660	63	15	15	13	18
Tarno	TRO	1	2.41	412	70	22	25	33	33
Turtle River	TUV	1	0.84	261	36	12	10	29	11
Two Creeks	TWC	3	2.11	769	73	20	11	13	20
Ullrich	ULH	4	2.08	740	70	18	9	11	23
Vandal	VDL	5	1.69	827	84	15	13	20	19
Vita	VIT	2	1.16	345	28	7	11	15	10
Valley	VLY	5	2.04	713	82	21	16	18	26
Varcoe	VRC	18	1.98	695	68	20	13	17	24
Vartel	VTL	1	1.54	1080	87	15	13	20	16
Woodfield	WDF	1	2.14	810	81	19	22	24	21
Wintergreen	WGE	3	0.87	220	18	14	8	17	8
Wheatland	WHL	11	1.59	636	40	10	7	11	13
Winkler	WIK	2	2.45	481	83	28	13	11	28
Waskada	WKD	12	2.09	790	68	17	15	18	22
Wampum	WMP	1	1.00	228	21	10	4	10	6
Woodridge	WOG	10	1.13	659	41	10	7	13	7
Woodmore	WOM	2	0.95	345	29	9	12	15	12
Wentland	WTD	3	1.30	369	57	18	12	27	18
Waitville	WTV	3	1.80	435	38	14	8	7	22
Wolverton	WVT	1	2.20	232	92	28	9	13	22
Willowbend	WWB	2	2.66	742	77	23	15	11	25
Willowcrest	WWC	6	1.04	279	29	7	7	12	11
Wellwood	WWD	14	2.25	655	78	20	13	17	20
Wawanesa	WWS	1	0.98	320	44	9	15	28	10
Zaporoza	ZAP	1	1.97	713	---	21	19	23	23
Zinman	ZIM	5	1.91	1105	62	17	16	14	24
Zaplin	ZPI	1	2.07	1344	72	17	19	16	23
Zarnet	ZRT	1	1.37	416	56	15	14	27	14

Table 7. Effects of soil and environmental conditions on trace element availability *

Element	Soil and Environmental Conditions Influencing Mobility and Availability		
	Effect of pH	Effect of redox conditions	Other factors affecting mobility
Arsenic - As	- increased mobility and availability in soil with decreasing pH.	- subject to methylation under any redox conditions, resulting in atmospheric release of As.	- adsorbed by hydroxides, clays and organic matter. - arsenate ions may be retained by iron oxides.
Cadmium - Cd	- most mobile at pH 4.5-5.5. - immobility of Cd in alkaline soils may be reduced at very high pH's by the formation of $CdOH^+$, which is not readily adsorbed.	- under oxidation conditions, Cd will form minerals and accumulate in phosphate and biolith deposits.	- Cd forms complex ions and organic chelates, its content in solution is low.
Chromium - Cr	- Cr^{3+} is only slightly mobile under acid conditions and is almost completely precipitated under pH 5.5.	- presence of organic matter promotes reduction of Cr^{6+} to Cr^{3+}, decreasing mobility. - presence of Mn oxides promotes oxidation of Cr^{3+} to Cr^{6+}, increasing Cr availability and toxicity.	-Cr^{6+} can be adsorbed by clays and hydrous oxides.
Cobalt - Co	- mobility increases with decreasing pH. - pH also affects the adsorption of Co by Mn minerals.	- mobility is greater under oxidizing conditions.	- adsorbed on iron, manganese and clay minerals. - the presence of Mn oxide minerals determines the Co distribution in the soil.
Copper - Cu	- solubility increases with decreasing pH. - solubility of all forms of Cu decreases at pH 7-8. - mobility may increase at high pH due to Cu^{2+} complex formation, which may increase overall Cu availability.	- mobility in reduced soils is low.	- subject to adsorption, precipitation, organic chelation and complexation and microbial fixation. - Cu is tightly held on inorganic and organic exchange sites. - precipitates with sulfides, carbonates and hydroxides. - the bulk of Cu adsorption is on Fe and Mn oxides.

Table 7. Effects of soil and environmental conditions on trace element availability *

Element	Soil and Environmental Conditions Influencing Mobility and Availability		
	Effect of pH	**Effect of redox conditions**	**Other factors affecting mobility**
Iron - Fe	- mobility of Fe increases with decreasing pH. - Fe has a high affinity for soluble organic chelates which may result in higher solution Fe levels than otherwise possible at normal pH's.	- reducing conditions increase the Fe solution concentration and therefore availability.	- solubility of Fe is affected mainly by hydrolysis and complexation. - Fe precipitates as oxides and hydroxides, substitutes for Al and Mg in minerals, and complexes with organic ligands.
Lead - Pb	- Pb is most available under acid conditions.	- in association with Mn oxides, the solubility of Pb decreases as Pb^{2+} is oxidized to Pb^{4+}.	- mainly associated in soil with organic matter, clay minerals and oxides of Mn, Al, and Fe. - there is limited availability of Pb in all soils unless the cation exchange capacity (CEC) is saturated or lead is present in soluble organic complexes.
Manganese - Mn	- as pH decreases, Mn solubility increases to the point that it may be present in toxic levels at acid pH's, while most basic and neutral soils are potentially deficient.	- solubility increases under reducing conditions in which Mn is present as Mn^{2+}, and decreases under oxidizing conditions. - Mn rapidly switches between reduced and oxidized states under all soil conditions.	- forms oxides and hydroxides and may form complex or simple ions in solution. - Mn accumulates in surface soils due to fixation by organic matter.
Mercury - Hg	- adsorption varies with pH, and is highest at pH 4-5. - in an acid environment, Hg may leach in organic compound form. - in a neutral to alkaline environment, inorganic Hg may be leached.	- Hg is persistent in aerobic soils but is partly converted to soluble monomethyl and gaseous dimethyl Hg complexes under waterlogged or flooded conditions.	- accumulation is controlled by complex formation and precipitation. - Hg tends to be higher in organic soils as it is bound by humus.
Molybdenum - Mo	- Mo solubility increases with increasing pH.	- mobility is higher in poorly drained soils.	- Mo anions produced upon weathering can be precipitated by organic matter, calcium carbonate and several cations: Pb^{2+},Cu^{2+}, Zn^{2+}, Mn^{2+}, and Ca^{2+}. - adsorbed by Fe, Al and Mn hydrous oxides.

Table 7. Effects of soil and environmental conditions on trace element availability *

Element	**Soil and Environmental Conditions Influencing Mobility and Availability**		
	Effect of pH	**Effect of redox conditions**	**Other factors affecting mobility**
Nickel - Ni	- Ni mobility increases as pH decreases.	- Ni mobility is very low under reducing conditions.	- soils with high CEC have low Ni availability. - Ni precipitates with Fe and Mn oxides, and is adsorbed onto clay and organic fractions.
Selenium - Se	- bioavailability increases with increasing pH.	- oxidized soil conditions increase Se availability.	- Se availability is modified by complexation, chelation and the presence of organic compounds and is very low in Fe rich soils.
Silver - Ag	- mobility increases with humus decomposition, which occurs as soil pH decreases. - mobile Ag complexes exist at pH<4.	- Ag precipitates under reduced conditions, and is more mobile under oxidizing conditions.	- significantly adsorbed by Mn oxides. - Ag is strongly adsorbed and complexed by humic substances. - Ag precipitation is encouraged by the presence of sulfur.
Vanadium - V	- most mobile in alkaline or neutral soils.	- V is basically immobile under reducing conditions.	- V can form complexes with organic matter, Fe oxides and clay minerals at low pH's.
Zinc - Zn	- high mobility of Zn at pH<7 may lead to leaching in sandy soils. - at high soil pH, Zn forms insoluble compounds and availability will be restricted.	- solubility of Zn decreases under reducing conditions.	- Zn is adsorbed by clay minerals. - it can be fixed by Al and Fe oxides as the pH increases.

*Sources for the information in this table are given in the individual description of each element in the Results and Discussion section of this report.

Table 8. Nutritional value of trace elements for plants and animals *

Element	Biological Functions	Deficiency: Symptoms and Limits	Toxicity: Symptoms and Limits
Ag	None known.	No known requirement for plants or animals.	High level of toxicity to plants (5-10 ppm on a dry weight basis), but toxic levels are not frequently found. Silver does not tend to biomagnify and bioconcentration factors are low. In humans, large amounts of silver will cause argyria: a blue-gray discolouration of eye, skin and mucous membranes. It is relatively harmless to higher life forms.
As	None known in animals. Constituent of phospholipid in algae and fungi.	No known requirements for higher plants or animals.	As is second only to Pb as a major toxicant to domestic animals. Limits are 50 ppm of feed for inorganic As and 100 ppm for organic As. Symptoms include weakness, gastrointestinal disturbances and kidney impairments. Toxic to plants at levels of 25-85 ppm total As in soil. Symptoms of plant toxicity include plasmolysis, leaf wilting and necrosis of leaf tips and margins. As biomethylates to form compounds resistant to oxidation which increases its resistance time in the environment. There is no evidence of biomagnification in the food web.
Cd	None known.	No known requirements for plants or animals.	Toxic to plants in excessive amounts (5-30 ppm dry weight). Maximum acceptable content of feed for livestock is 0.5 ppm Cd. Because Cd accumulates in the liver and kidneys of livestock, it may be passed on to humans by consumption of the organs.
Co	Essential for ruminant nutrition because it is required by rumen microorganisms to synthesize vitamin B^{12}. Required by rhizobia in symbiotic N_2 fixation. Not known to be required by higher plants.	Deficiency for ruminants occurs when total soil Co levels are below 5 ppm. Symptoms include loss of appetite and emaciation.	Co is not toxic to animals at concentrations well above those in the natural environment. Excessive amounts of Co (15-50 ppm, dry weight) are toxic to most plants and can cause white dead margins at leaf tips and interveinal chlorosis. Toxicity is not often found in nature.

Table 8. Nutritional value of trace elements for plants and animals - continued

Element	Biological Functions	Deficiency: Symptoms and Limits	Toxicity: Symptoms and Limits
Cu	Essential to all organisms. Cu is a cofactor in redox enzymes and O_2 transport pigments.	Plant deficiencies occur at soil levels below 1-2 ppm total soil Cu. Symptoms include wilting, disturbances in pollen and fertility development. Copper deficiencies in animals occur particularly in sheep and can result in morbidity and death.	Cu toxicity in plants is uncommon naturally, but may occur with excessive use of fungicides or in mine waste areas, if dry weight plant levels reach 20-100 ppm.. Maximum acceptable levels in feed is generally 15 ppm but varies with species. Cu tends to accumulate in the liver of livestock, which could be of concern to the consumer.
Fe	Essential to all organisms. Cofactor in enzymes and heme proteins.	Low levels of available soil Fe lead to iron chlorosis in plants. Deficiencies in animals are rarely observed, but may occur if feed contains less than 50-100 ppm Fe on a dry weight basis.	Toxicity levels for plants are variable among species, and have not been reported for plants under natural conditions. Symptoms include dark green foliage, stunting of tops and roots and dark brown or purple leaves.
Hg	None known.	No known requirements for plants or animals.	Toxicity occurs in plants at levels of 1-3 ppm dry weight. Symptoms include severe stunting of seedlings and roots and chlorosis. Mercury accumulates in tissues of livestock, posing a health hazard for human consumption.
Mn	Essential to all organisms. Cofactor in numerous enzymes. Involved in photosynthesis.	Deficiency problems arise in plants at dry weight levels of less than 10-30 ppm and can lead to necrosis and reduced turgor. Mn deficiency is not common in animals, although it can be a problem in poultry because they have higher Mn requirements.	Toxicosis occurs in plants at levels of 400-1000 ppm and is the cause of such diseases as crinkle-leaf disease in cotton and stem streak necrosis in potatoes.
Mo	Essential to almost all organisms. Cofactor in N_2 fixation and NO_3 reduction.	Deficiency problems occur in plants at levels of 0.1-0.3 ppm. For livestock, deficiencies can lead to Cu toxicicity, as animals must maintain a Cu:Mo ratio of 2:1.	Molybdenosis occurs in animals when dietary intake of Cu and Mo does not occur in a 2:1 Cu:Mo ratio. This situation may occur if Mo content of feed is > 5 ppm. Plants exhibit toxicosis at levels of 10-50 ppm, but this is rare under field conditions.

Table 8. Nutritional value of trace elements for plants and animals - continued

Element	Biological Functions	Deficiency: Symptoms and Limits	Toxicity: Symptoms and Limits
Ni	Essential in livestock, may be essential to humans and plants.	Deficiencies are not likely to occur in plants because the requirement, if any is thought to be very small. Deficiencies are unlikely in animals because the natural Ni intake is higher than levels shown to cause deficiencies.	Excessive amounts of Ni (10-100 ppm, dry weight) lead to a suppression of plant growth. This can occur on naturally nickel rich soils.
Pb	None known.	No known requirements for plants or animals.	Toxicity in plants can occur at levels of 30-300 ppm, and result in stunted foliage, roots and reduced germination and growth rate. This is seldom observed under field conditions. Pb accumulates in the skeleton to a critical maximum, then lead increases in circulation until poisoning occurs. Pb also tends to accumulate in the liver and kidneys of livestock, leading to potential poisoning of humans with consumption. Toxicosis in animals occurs at levels of 30 ppm Pb in the diet for most species.
Se	Essential to mammals and some plants.	If feed contains less than 0.06 ppm Se, livestock may develop white muscle disease. Human deficiency can lead to cardiomyopathy and tubular bone changes, but the level of requirement is unknown.	Se toxicity in plants is unlikely under natural conditions. Levels toxic to animals are those that exceed 5 ppm Se in feed, which could lead to “alkali disease” and “blind staggers” in livestock. Toxic levels in humans can lead to miscarriage, malformation of children and dermatitis.
V	Required in lipid, tooth and bone metabolism in some animals. Not essential for higher plants.	Animals require 50-500 ppb in food for optimum growth.	Toxic to plants when present in excess amounts (5-10 ppm). V can interfere with the utilization of cellular ATP in animals if it is present in excessive amounts.

Table 8. Nutritional value of trace elements for plants and animals - continued

Element	Biological Functions	Deficiency: Symptoms and Limits	Toxicity: Symptoms and Limits
Zn	Essential to all organisms. Cofactor in numerous enzymes.	Can occur in livestock and plants. Poultry and ruminants require 35 ppm Zn in feed and swine require 100 ppm. Plants require levels above 10-20 ppm, less Zn will lead to interveinal chlorosis, retarded growth and violet red leaf discolouration.	Toxicity can occur at 500 ppm for calves and 600 ppm for sheep. Levels above 100-400 ppm can lead retarded plant growth and necrosis in root tips.

*Sources for the information in this table are given in the individual description of each element in the Results and Discussion section of this report.