Canadian Soil Quality Guidelines for

Cadmium: Environmental

Supporting Document — Final Draft
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NOTICE

This final draft document provides the information supporting the derivation of environmental soil quality guidelines for cadmium. Development of these soil quality guidelines was initiated through the National Contaminated Sites Remediation Program (NCSRP) which officially ended in March 1995. Given the need for national soil quality guidelines for contaminated sites management and many other applications, development was pursued under the direction of the CCME Soil Quality Guidelines Task Group after the end of the NCRSP.

This document is a working document that was released shortly after the publication of "A Protocol for the Derivation of Environmental and Human Health Soil Quality Guidelines" (CCME 1996). The CCME recognizes that some refinements or changes to the Protocol may become necessary upon application and testing. If required, amendments to the Protocol will be made and the guidelines will be modified accordingly. For this reason guidelines are referred to in this document as CCME Recommended Guidelines. Readers who wish to comment or provide suggestions on the Protocol or on the guidelines presented in this document should send them to the following address:

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This document is a supporting technical document. It is available in English only. A French Abstract is given on page vii.

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ABSTRACT

Canadian environmental quality guidelines, developed under the auspices of the Canadian Council of Ministers of the Environment (CCME), are numerical concentrations or narrative statements recommended to support and maintain designated resource uses. CCME Canadian soil quality guidelines can be used as the basis for consistent assessment and remediation of contaminants at sites in Canada.

This report was prepared by the Guidelines Division of the Science Policy and Environmental Quality Branch (Environment Canada), which acts as Technical Secretariat for the CCME Soil Quality Guidelines Task Group. The Guidelines were derived according to the procedures described in *A Protocol for the Derivation of Environmental and Human Health Soil Quality Guidelines* (CCME 1996).

Following the introduction, chapter 2 presents chemical and physical properties of cadmium (Cd) and a review of the sources and emissions in Canada. Chapter 3 discusses cadmium's distribution and behavior in the environment while chapter 4 reports the toxicological effects of cadmium on microbial processes, plants, and animals. These informations are used in chapter 5 to derive soil quality guidelines for cadmium to protect environmental receptors in four types of land uses: agricultural, residential/parkland, commercial, and industrial.

The following soil quality guidelines are recommended by the CCME based on the available scientific data. The environmental soil quality guideline (SQG_E) relative to cadmium for agricultural land use is 3.8 mg Cd·kg^{-1} soil. It is 10 mg Cd·kg^{-1} soil for residential/parkland land uses and 27 mg Cd·kg^{-1} soil for commercial and industrial land uses. These environmental soil quality guidelines are optimized for soils within the pH range of 4 to 8.1 as the toxicological studies on which they are based were conducted within this pH range.

RÉSUMÉ

Les recommandations canadiennes pour la qualité de l'environnement, élaborées sous les auspices du Conseil Canadien des Ministres de l'Environnement (CCME), sont des concentrations ou des énoncés décrivant les limites recommandées dans le but d'assurer le maintien et le développement durable d'utilisations désignées des ressources. Les recommandations canadiennes pour la qualité des sols proposées par le CCME peuvent être utilisées comme base pour l'uniformisation des processus d'évaluation et d'assainissement des terrains contaminés au Canada.

Le présent document a été préparé par la Division des Recommandations de la Direction de la Qualité de l'Environnement et de la Politique Scientifique (Environnement Canada), qui agit comme secrétaire technique pour le Groupe de Travail du CCME sur les Recommandation pour la qualité des sols. Les Recommandations ont été élaborées selon les procédures décrites dans le *Protocole d'élaboration de recommandations pour la qualité des sols en fonction de l'environnement et de la santé humaine* (CCME 1996).

Faisant suite à une brève introduction, le chapitre 2 présente les propriétés physiques et chimiques du cadmium (Cd) de même qu'un survol des sources et des émissions au Canada. Le chapitre 3 discute du devenir et du comportement de cette substance dans l'environnement alors que le chapitre 4 rapporte ses effets toxicologique sur les processus microbiens, les plantes et les animaux. Ces informations sont utilisées au chapitre 5 afin d'élaborer des recommandations pour la qualité des sols relatives au cadmium en vue de la protection de l'environnement dans le cadre de quatre types d'utilisations de terrains: agricole, résidentiel/parc, commercial et industriel.

Les recommandation pour la qualité des sols suivantes, proposées par le CCME, sont fondées sur les données scientifiques disponibles. Aux niveau des terrains à vocation agricole, la recommandation pour la qualité des sols relative au cadmium en vue de la protection de l'environnement (RQS_E) est de 3.8 mg de $Cd\cdot kg^{-1}$ de sol. Pour les terrains à vocation résidentielle/parc, elle est de 10 mg de $Cd\cdot kg^{-1}$ de sol et pour les terrains à vocation commerciale et industrielle, elle est de 27 mg de $Cd\cdot kg^{-1}$ de sol. Ces recommandations pour la qualité des sols en vue de la protection de l'environnement sont à leur optimum dans des sols avec pH entre 4 et 8.1 puisque les études toxicologiques utilisées pour leur élaboration ont été effectuées dans ces mêmes conditions de pH.

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1. INTRODUCTION

The Canadian Council of Ministers of the Environment's (CCME) Canadian Environmental Quality Guidelines are numerical limits for contaminants intended to maintain, improve, or protect environmental quality and human health. CCME Canadian Soil Quality Guidelines can be used as the basis for consistent assessment and remediation of contaminants at sites in Canada along with CCME guidelines issued for the protection of water quality, sediment quality and tissue quality. In response to the urgent need to begin remediation of high priority "orphan" contaminated sites, an interim set of criteria were adopted from values currently in use in various jurisdictions across Canada (CCME 1991). Many of the interim soil remediation criteria do not have a complete supporting scientific rationale and are being updated based on current scientific information.

This report reviews the sources and emissions of cadmium, its distribution and behaviour in the environment, and its toxicological effects on terrestrial mammals, plants, and soil organisms. This information is used to derive guidelines for cadmium to protect ecological receptors according to the processes outlined in *A Protocol for the Derivation of Environmental and Human Health Soil Quality Guidelines* (CCME 1996) for agricultural, residential/parkland, and commercial/industrial land uses.

The values derived here are ecological effects-based soil quality guidelines and are intended as general guidance. Site-specific conditions should be considered in the application of these values. The values may be applied differently in various jurisdictions, therefore the reader should consult the appropriate jurisdiction for application of the values.

2. BACKGROUND INFORMATION

2.1 Physical and Chemical Properties

Cadmium (Cd) is a metal of subgroup IIb of the transition series in the periodic table. It is a soft-white, blue-tinged, lustrous metal that melts at 320.9°C and boils at 765°C (Eisler 1985). Its atomic number and molecular weight are 48 and 112.40 g/mol, respectively. Elemental cadmium is insoluble in water, and the solubility of cadmium salts varies: cadmium chloride is very soluble (140 $g \cdot 100\ mL^{-1}$ water), whereas cadmium sulphide is only sparingly soluble (0.00013 $g \cdot 100\ mL^{-1}$ water) (CRC 1992). It is among the least abundant trace elements and is seldom found in pure minerals.

Cadmium predominantly occurs in nature as the divalent cation (Cd^{2+}). Chemically, cadmium closely resembles zinc and occurs in almost all zinc ores both as a sulphide and a carbonate. In the environment, cadmium may be present in a variety of inorganic and organic compounds, depending on such factors as the medium considered and ambient environmental conditions. The physical and chemical properties of cadmium and its principal salts are listed in Table 1.

Cadmium ranks as the 64th most abundant element in the earth's crust, with an average crustal abundance of 0.2 $mg \cdot kg^{-1}$ (Taylor 1964). The highest concentrations tend to occur in shales and marine phosphorites, with levels up to 90 $mg \cdot kg^{-1}$ and 340 $mg \cdot kg^{-1}$ reported, respectively (WHO 1984a). Typical concentrations of cadmium in igneous, metamorphic, and sedimentary rocks are 0.001–1.8 $mg \cdot kg^{-1}$, 0.04–1.0 $mg \cdot kg^{-1}$, and 0.3–11 $mg \cdot kg^{-1}$, respectively (WHO 1984a).

2.2 Analytical Methods

The most common methods used in programs for metals research and monitoring involve atomic absorption spectroscopy (AAS) and inductively coupled plasma–atomic emission spectroscopy (ICP–AES) (Skoog et al. 1988). Typical detection limits for modern instruments measuring cadmium in solution are 1 $\mu g \cdot L^{-1}$ for flame AAS, 0.1 $\mu g \cdot L^{-1}$ for graphite furnace AAS, 0.8 $\mu g \cdot L^{-1}$ for flame AES, and 2 $\mu g \cdot L^{-1}$ for ICP–AES (Skoog et al. 1988).

The analysis of cadmium in soils and sediments is routinely measured by hot digestion of the sample with concentrated acids (Jackson and Alloway 1991; Singh and Narwal 1984; Xian 1989). Recent interest in measuring "bioavailable" metal species in soils and sediments has initiated research into less severe digestion techniques, which may allow the bioavailable metal fractions to be operationally defined. There is no consensus as to which technique is the most appropriate, although variations on the sequential extraction procedure proposed by Tessier et al. (1979) appear to be the most common.

One method of analyzing soil for cadmium has been recommended by the CCME (1993) in an effort to promote consistency within the National Contaminated Sites Remediation Program (NCSRP). U.S. EPA method 6010 (inductively coupled plasma–atomic emission spectroscopy) prescribes a sequential sample preparation using nitric acid, hydrogen peroxide, and hydrochloric acid and requires an inductively coupled argon plasma emission spectrometer capable of background correction. Detection limit for this method has been estimated at 4 $\mu g \cdot L^{-1}$ in solution. Following corrections for a 1g soil sample digested with the final extract being diluted to 100 mL, a detection limit in soils of 0.4 mg $Cd \cdot kg^{-1}$ would be calculated.

2.3 Production and Uses in Canada

Production and Canadian Exports and Imports

Cadmium is recovered from the fumes produced during the roasting of zinc ores and concentrates and from the precipitates obtained during the purification of zinc sulphate (Brown 1977). Global production of refined cadmium metal for 1990 was estimated at 21 800 t, which represents an increase of approximately 5% over 1989 (Hoskin 1991). Canada is the fourth largest producer of cadmium in the world, with an output of approximately 1 865 t in 1991 (Koren 1992). The annual production of cadmium in Canada has been relatively stable since 1984, with the mean level for this period near 1 570 t annually (Koren 1992). An estimated 75% (1 070 t) of the Canadian production of cadmium was exported in 1990, mainly to the United States, Japan, and France (Hoskin 1991).

Imports of cadmium into Canada in 1991 have been estimated at 116.3 t (Koren 1992). It may be conservatively estimated that the total amount of cadmium metal "entering" Canada in the form of nonexported domestic production and imported products in 1990 was approximately 700 t.

Industrial Uses

There are five main industrial uses of cadmium: nickel/cadmium batteries, coatings, pigments, stabilizers in plastics and synthetic products, and alloys (Hoskin 1991). Domestic industrial consumption in Canada has been increasing steadily in recent years: 18.9 t in 1987; 20.0 t in 1988; 28.8 t in 1989, and 35.2 t in 1990 (Hoskins 1991; Koren 1992). Cadmium compounds are used in the production of polyvinyl chloride (PVC) and picture tubes for television sets. Cadmium is also present in cadmium–silver solders, telephone and trolley wires, metal sheets for automobile radiators, control rods and shields for nuclear reactors, motor oils, and curing agents for rubber (CCREM 1987). In Canada, electroplating accounted for 61%–77% of the total consumption, with soldering, alloys, chemicals, and pigments making up the remainder (Hoskin 1991).

Agricultural Uses

Cadmium is registered under the Pesticide Control Act for use as a fungicide in turf grass production. Three pesticide products that contain cadmium as the active ingredient are currently marketed in Canada: C-A-D Turf Fung, Green Cross Cadmium Liquid Turf Fungicide, and Caddy Liquid Turf Fungicide. Each of these products contains 20.1% cadmium chloride (Agriculture Canada 1992).

2.4 Levels in the Canadian Environment

2.4.1 Anthropogenic Inputs into the Canadian Environment

The most recent data on anthropogenic inputs was compiled for 1982 and indicate that 322 tonnes of cadmium were released to the Canadian environment as a result of anthropogenic domestic activities. Approximately 80% of emissions were attributed to industrial processes associated with smelting and refining, 16% were due to stationary fuel combustion, 2% resulted from transportation sources and solid waste incineration was responsible for 2% of emissions.

In recent years, smelting and refining operations contributed roughly 64% of the cadmium emissions to air and almost 90% of the total emissions to the environment (Jaques 1987; McLatchie 1991). Data compiled by McLatchie (1991) indicate that six smelters account for virtually all of the cadmium emitted by this industry. These smelters are Canadian Electrolytic Zinc (Noranda, Quebec), Hudson Bay Mining and Smelting (Flin Flon, Manitoba), Falconbridge (Kidd Creek, Ontario), Noranda (Horne, Nova Scotia), Brunswick Mining and Smelting (Bathurst, New Brunswick), and Cominco (Trail, British Columbia).

2.4.2 Distribution of Cadmium in the Canadian Environment

Air

The limited available data on the levels of cadmium in the Canadian atmosphere suggest that concentrations are generally quite low. In 1982, mean concentrations of cadmium in southern, central, and northern Ontario were 420, 460, and 310 $pg{\cdot}m^{-3}$, respectively. The highest levels reported in the province were measured in the vicinity of Colchester (650 $pg{\cdot}m^{-3}$), Wilkesport (720 $pg{\cdot}m^{-3}$), Golden Lake (630 $pg{\cdot}m^{-3}$), and Gowganda (850 $pg{\cdot}m^{-3}$) (Chan et al. 1986).

Soil

Table 2 presents a summary of cadmium levels found in soil at various sites across Canada. The available data indicate that background concentrations of cadmium in Canada range from not detectable (Whitby et al., 1978) to as high as 8.1 $mg{\cdot}kg^{-1}$ (Frank et al., 1986). Recently, background levels of cadmium have been established in Ontario for agricultural and residential/parkland land uses at 1.0 $mg{\cdot}kg^{-1}$ (OMEE 1994). In a study on cadmium levels in A horizon soils, Garrett (1994) reported an environmental baseline concentration of 0.3 $mg{\cdot}kg^{-1}$ for the Canadian prairies. The vast majority of the samples (99%) had cadmium levels below 0.7 $mg{\cdot}kg^{-1}$ (Garrett 1994).

The available Canadian data also emphasize the potential effects of anthropogenic activities on cadmium levels in soil. While the highest concentrations have been reported in the vicinity of lead–zinc smelters, elevated levels of cadmium have also been observed as the result of the disposal of sewage sludge, combustion of fossil fuels, and weathering of galvanized metals. In British Columbia, elevated levels of cadmium have been reported in soils from the Columbia River valley in the vicinity of the Cominco lead–zinc smelter. Average cadmium concentrations in surface litter within 10 km of the smelter were 17.1 $mg{\cdot}kg^{-1}$ (John 1975). Data collected in the vicinity of a copper smelter in Flin Flon, Manitoba, indicate significant contamination with cadmium. The mean concentration in garden soils in this areas was 5.19 $mg{\cdot}kg^{-1}$, and ranged from 3.2 to 13 $mg{\cdot}kg^{-1}$ (Pip 1991). Whereas background concentrations of cadmium in Ontario soils are fairly low, higher levels have been reported near known sources of cadmium, such as power transmission towers (Jones et al. 1988), sewage sludge application sites (Frank et al. 1976; Webber and Shamess 1987), and urban roads (Van Loon et al. 1973). Data collected in the vicinity of the smelter at Rouyn-Noranda in Quebec indicate that soils are highly contaminated with cadmium. Within 1–3.7 km of the smelter, cadmium levels ranged from 54 to 66 $mg{\cdot}kg^{-1}$ in the top 15 cm of soil. These are the highest cadmium concentrations recorded in Canadian soils.

Sediment

Background levels of cadmium in freshwater sediments in Canada appear to be uniformly low. However, extremely high concentrations have been reported in severely contaminated watercourses. The highest level in Canada, 1 100 $mg{\cdot}kg^{-1}$, was reported in the vicinity of a hard-rock mining operation on Myra Creek, Vancouver Island (Garrett 1985). Elevated cadmium concentrations of

178, 33, and 20.5 $mg\cdot kg^{-1}$ have been reported in the Columbia River (Garrett 1985), the Detroit River (Nichols et al. 1991), and Hamilton Harbour (Mayer and Manning 1990), respectively.

Levels of cadmium are generally lower in marine sediments than in freshwater sediments. Uthe et al. (1986) reported concentrations of up to 37 $mg\cdot kg^{-1}$ in sediments from Belledune Harbour in New Brunswick; however, much lower levels, 0.01–3.76 $mg\cdot kg^{-1}$, have been measured in other locations on the Atlantic coast (Loring 1982; Ray and White 1977). On the Pacific coast, elevated levels of cadmium in sediment up to 7.4 $mg\cdot kg^{-1}$ have been reported in Vancouver Harbour (Goyette and Boyd 1989)and up to 8.2 $mg\cdot kg^{-1}$ for Ucluelet Inlet (Pedersen et al. 1989).

Water

Data from across Canada suggest that cadmium concentrations are generally lower than 0.1 $\mu g\cdot L^{-1}$ in freshwater systems. Significantly higher levels, however, have been observed in the vicinity of industrial developments such as smelters. For example, Smith (1987) reported cadmium concentrations in the Columbia River averaging 0.6 $\mu g\cdot L^{-1}$ within a range of 0.05–1.7 $\mu g\cdot L^{-1}$ over the period 1975–1977. Levels of cadmium of up to 0.587 and 0.32 $\mu g\cdot L^{-1}$ have also been observed in lakes in the Sudbury area (Stephenson and Mackie 1988) and in Lake Erie (Allan and Ball 1990), respectively.

Concentrations of cadmium in marine waters, as in freshwater systems, are generally lower than 0.1 $\mu g\cdot L^{-1}$. However, contamination from industrial activities has resulted in extremely high levels in several locations. Loring et al. (1980) reported that Belledune Harbour, New Brunswick, had cadmium levels ranging from 25.5 to 125 $\mu g\cdot L^{-1}$ near the lead smelter outfall. Much lower levels of 0.16–2.5 $\mu g\cdot L^{-1}$ were observed in nearby coastal areas. Subsequent installation of a waste treatment system reduced cadmium concentrations to less than 0.17 $\mu g\cdot L^{-1}$ in the harbour (Uthe et al. 1986).

2.5 Existing Criteria, Guidelines, and Standards

Existing criteria, guidelines, and standards for cadmium in soil from provincial and international agencies are summarized in Table 3.

3. ENVIRONMENTAL FATE AND BEHAVIOUR

Cadmium being an element cannot be degraded in the environment. As such, the fate of cadmium is dependent on a suite of physicochemical and biological factors that influence cycling among biotic and abiotic components of the environment. The most important of these factors are pH and the presence and abundance of organic materials, hydroxides, clay minerals, cations, and complexing ligands. Cadmium has a high affinity for negatively charged surfaces associated with clay minerals, hydroxides, organic compounds, and carbonates. Consequently, it tends to be removed rapidly from solution. Although surface soils and aquatic sediments may act as temporary sinks for cadmium, changes in environmental conditions have the potential to remobilize and transport it to other compartments of the ecosystem.

3.1 Soil

A variety of factors influence the mobility of cadmium in soils with pH and soil type, including particle size, content of metal oxides, hydroxides and oxyhydroxides, and organic matter content, being probably the most important. Numerous studies have identified soil pH as an important factor in influencing the mobility of cadmium in soil (Chanmugathas and Bollag 1987; Christensen 1989b; Eriksson 1989; Lodenius and Autio 1989), and most studies indicate that significant movement of cadmium within the soil matrix and into other media is likely to occur under acidic conditions. A number of processes also have the potential to affect the fate of cadmium in soils, including aeolian transport (wind erosion), fluvial transport, leaching, and uptake by terrestrial organisms.

Soils are particularly important in the attenuation of cadmium since they have both mineral and organic constituents involved in metal retention (Evans 1989). Many studies have shown that clay minerals (Christensen 1984a, 1984b; Inskeep and Baham 1983; McBride et al. 1981), metal oxides, hydroxides, and oxyhydroxides (Benjamin and Leckie 1981a, 1981b; Bruemmer et al. 1988; Fu et al. 1991), and organic matter (Blume and Brummer 1991) are involved in the immobilization of cadmium in soils. However, the presence of high concentrations of dissolved organic matter in soil leachates can also enhance cadmium mobility and, as such, pose a risk to groundwater quality (Bollag and Czaban 1989; Christensen 1989a; Singh 1990).

Microorganisms may have either an inhibitory or a stimulatory effect on the mobility of cadmium in soil. Organic substances produced by some soil microorganisms may chelate and effectively immobilize cadmium (Bollag and Czaban 1989). In addition, microbial production of hydrogen sulphide can result in the formation of insoluble cadmium sulphides, which are very stable (Bollag and Czaban 1989). However, microbial decomposition of organic matter or metal sulphides may result in the release of cadmium from stable complexes and, as such, increase its overall mobility (Cole 1979). The degree of mobilization is dependent on soil type, aeration, and moisture content. Under certain circumstances, lateral transport, including aeolian and fluvial transport, has been shown to be an important environmental process affecting the fate of cadmium in soils. Bell et al. (1991) reported significant losses of cadmium within one year from soils treated with sewage sludge or metal salts and suggested that the mixing of surficial soils with subsurface soils and lateral transport were the most important factors contributing to these losses. McGrath and Lane (1989) also suggested that lateral transport due to mechanical cultivation and erosion can significantly affect the fate of cadmium in soils. Nriagu and Pacyna (1988) calculated that wind erosion of soils constituted one of the largest natural cadmium fluxes to the atmosphere.

3.2 Freshwater Ecosystems

Gardiner (1974) as well as Vuceta and Morgan (1978) found that a substantial proportion of cadmium in rivers and lakes is there as free Cd^{2+}; however, pH complexation by organic ligands and adsorption to particles will affect the speciation. Most of the cadmium present in freshwater systems (up to 90%) occurs in the dissolved phase (i.e., <0.45 µm). However, at very high concentrations of suspended particulate matter (e.g., higher than 200 $mg \cdot L^{-1}$), adsorbed cadmium predominates as a result of particle scavenging (Lum 1987). Cadmium entrained by particles and carried to bottom sediments is often released after oxidation or decomposition and subsequently recycled into overlying waters. Concentrations of cadmium in lake waters are strongly dependent on pH, and are consistently higher in acid lakes than in those of circumneutral systems (Steinnes 1990).

3.3 Marine Ecosystems

Most of the cadmium entering the ocean from continental runoff is temporarily retained in estuaries, although 85% or more of the dissolved cadmium may eventually enter the marine pelagic environment (Bewers et al. 1987). Dissolved forms of cadmium predominate in coastal waters and may constitute 60% or more of the total cadmium (Lum 1987). Cadmium has a very high affinity for chloride to wich the majority of the cadmium in seawater is associated (Gunneriusson and Sjöberg 1991; Hahne and Kroontje 1973; Zirino and Yamamoto 1972), with approximately 35% occurring as $CdCl^+$, 37% as $CdCl_2^\circ$, and 26% as $CdCl_3^-$ (Bewers et al. 1987). In general, less than 3% of the cadmium in seawater occurs in the cationic form (Cd^{2+}).

A significant proportion of the total cadmium entering the ocean via atmospheric deposition or river runoff is eventually deposited in deep ocean sediments. However, perhaps more so than in any other environment, there appears to be a consistent pattern of recycling of the cadmium pool in oceans. The residence time for cadmium in the mixed layer of the Pacific Ocean is very short (less than 0.1 year) compared to that of other metals (Bewers et al. 1987). Much of the total cadmium in seawater (up to 60%) is bound to or incorporated in organic matter, and, as such, is constantly being removed from surface waters through biogenesis and sinking (Bewers et al. 1987). As a result, surface waters (shallower than 500 m) are typically depleted of cadmium. Upon decomposition at depth or through oxidation in sediments, much of the cadmium associated with organic matter is released to overlying waters or recirculated to the euphotic zone via vertical mixing (Bewers et al. 1987).

3.4 Atmosphere

Cadmium has a boiling point of 765 °C and, therefore, is not likely to volatilize except under extreme conditions (e.g., volcanoes and forest fires). However, anthropogenic activities, such as the roasting of zinc ores, high temperature incineration of sewage sludge, or the burning of fossil fuels, may release cadmium to the atmosphere (Kistler et al. 1987). Most of the cadmium particles, gases, and vapours emitted into the atmosphere are deposited fairly quickly, within 4 weeks, and generally within 1 000 km of the source (Bewers et al. 1987).

4. BEHAVIOUR AND EFFECTS IN BIOTA

One way to assess the potential hazards of cadmium-contaminated soils to terrestrial organisms is to examine effects-based toxicity studies. The LOEC endpoints reported in the toxicity tables represent the lowest–observed–effects concentration at which there was a statistically and biologically significant difference from controls, as reported by the author(s). If no such statistical tests were reproted by the author(s), the percentage of adverse effect, as compared to the controls, resulting from cadmium concentrations within the soil will be calculated by the CCME from the data presented by the author(s). This percentage of adverse effect is represented by an EC (effects concentration) endpoint in the toxicity tables. Actual EC_{xx} endpoints reported by the authors(s), such as EC_{50} or EC_{25} , will be presented as such without any calculation of a percentage of adverse effect. Measured concentrations and metal extraction methods are reported in the toxicity tables only if they involve a strong acid, such as HCl or HNO_3. Otherwise, the nominal concentrations are reported.

4.1 Soil Microbial Processes

Microbial toxicity studies selected for use in soil quality guidelines derivation are presented in Table 5, while additional microbial studies that were consulted but not used in guidelines derivation are presented in Table 4.

Naidu and Reddy (1988) reported that populations of bacteria and fungi were significantly reduced in clay soils containing 10 mg Cd·kg^{-1}. Similarly, large decreases in the abundance of fungi and cellulolytic microbes were reported in sandy soils at concentrations as low as 2.9 mg Cd·kg^{-1} (Kobus and Kurek 1990). Zibilske and Wagner (1982) reported reduction in populations of soil bacteria after a two-week exposure to soil amended with sewage sludge and cadmium. In addition to effects on free-living microorganisms, cadmium has been shown to inhibit the colonization of ectomycorrhizae on tree roots. Dixon and Buschena (1988) reported a 60% reduction in the colonization of ectomycorrhizae on the roots of white pine *(Pinus glauca)* at 2.0 mg Cd·kg^{-1}. Similar results on the colonization of ectomycorrhizae on red oak *(Quercus rubra)* and jack pine *(Pinus banksiana)* were observed at higher cadmium concentrations (10–50 mg·kg^{-1}) (Dixon 1988; Dixon and Buschena 1988).

There is some evidence that microorganisms exposed to metal-contaminated soils develop increased metal tolerance. Chaudri et al. (1992a) found that *Rhizobium leguminosarum* bv. *trifolii* isolated from a soil amended with sewage sludge was killed with an added cadmium concentration of 0.8 mg·L^{-1}, while the same microorganism isolated from an uncontaminated soil was killed at only 0.2 mg·L^{-1} added cadmium.

Soil metabolic processes are also likely to be impaired by cadmium. Significant decreases in the evolution of carbon dioxide from soils have been observed at concentrations as low as 2.6 mg Cd·kg^{-1} (Bond et al. 1976; Chang and Broadbent 1981; Cornfield 1977; Kobus and Kurek 1990; Reber 1989; Wilke 1991). Doelman and Haanstra (1984) reported a 47% reduction of soil respiration at a concentration of 1000 mg/kg while Lighthart et al. (1983) measured a 35 % inhibition of soil respiration at 562 mg/kg. Decreases in the rates of nitrogen fixation and other nitrogen cycle processes have been observed at fairly low levels of cadmium (2.0–10 $mg{\cdot}kg^{-1}$) in both short-term (48-h) and long-term (60-d) studies (Coppola et al. 1988; Kobus and Kurek 1990; Liang and Tabatabai 1977; Liang and Tabatabai 1978; Naidu and Reddy 1988; Wilke 1991; Wilke 1989). Soils amended with sewage sludge, and hence contaminated with cadmium, were found to have a 10 times decreased ability to fix molecular nitrogen (N_2) as compared to uncontaminated soils (Brookes et al. 1986). Chaudri et al. (1992b) found that after 18 months, a soil contaminated with 7.1 mg $Cd{\cdot}kg^{-1}$ exhibited no nitrogen fixation. Elevated cadmium levels have also been associated with inhibition of soil enzymatic processes, including dehydrogenase, arylsulphatase, and phosphatase activities. Effective concentrations (EC_{50}s) of cadmium for inhibition of arylsulphatase and phosphatase activities ranged from 121 to 1 798 $mg{\cdot}kg^{-1}$ (Haanstra and Doelman 1991) and from 230 to 9 870 $mg{\cdot}kg^{-1}$ (Doelman and Haanstra 1989), respectively. Zibilske and Wagner (1982) reported a reduction in ATP production in soils amended with sewage sludge and cadmium.

Physicochemical properties of soils influence, to a great extent, the chemical speciation and hence the bioavailability and toxicity of cadmium to soil microorganisms. Increasing the cation exchange capacity (CEC) of soils by amending them with clay minerals was shown to decrease cadmium toxicity to microbial survival and growth (Babich and Stotzky 1977b, 1977c). The incorporation of clay minerals into soils also decreased the lag in carbon mineralization that resulted from cadmium additions (Bewley and Stotzky 1983a, 1983b). The presence of soluble organics that can chelate cadmium has also been shown to result in decreased toxicity (Babich and Stotzky 1983, 1985; Lighthart 1980). Competition between cations normally present in the environment and the cationic form of cadmium is likely responsible for a decrease in cadmium toxicity (Babich and Stotzky 1983). Hart et al. (1979) found that the presence of iron reduced cadmium uptake by *Chlorella pyrenoidosa*, and Laborey and Lavollay (1977) reported that increased levels of calcium decreased cadmium toxicity to *Aspergillus niger*. Rother et al. (1982) measured no significant effect of cadmium-contaminated soils on the rate of nitrogen fixation. This was attributed to the presence of inorganic anions, sulphides (S^{2-}) and carbonates (CO_3^{2-}), and hence to the precipitation of cadmium sulphides and carbonates.

Research has shown that pH can also affect the toxicity of cadmium to soil microorganisms (Babich and Stotzky 1983, 1985). However, the results of studies have been contradictory because pH affects many aspects of the microorganism–metal system. Increasing pH has been shown to both increase (Babich and Stotzky 1977a, 1977c) and decrease (Hart and Scaife 1977; Singh and Pandey 1981) cadmium toxicity to microorganisms.

4.2 Terrestrial Plants

Metabolic Fate and Behaviour

Uptake rates of cadmium by terrestrial plants are variable and depend on the plant species (Kim et al. 1988; Kuboi et al. 1986), cadmium concentration in soil, and other factors influencing the bioavailability of cadmium in soils. Translocation of cadmium is not universal among plants, and research has shown accumulation of cadmium in the roots of some plants (Carlson and Ragsdale 1988; Mench et al. 1989) and in the leaves of others (Boon and Soltanpour 1992; Kim et al. 1988).

Toxicity

Plant toxicity studies selected for use in soil quality guidelines derivation are presented in Table 8, while additional plant studies that were consulted but not used in guidelines derivation are presented in Table 6.

Data on the acute toxicity (exposure period of $\leq$14 d) of soil-borne cadmium to terrestrial plants exist for four crop species grown in Canada: oats, tomatoes, lettuce, and turnips. These data suggest that terrestrial plants exhibit a rather narrow range of sensitivities to cadmium, with EC_{50} concentrations for growth ranging from 16 to 171 mg Cd·kg^{-1} dry soil. Adema and Henzen (1989) reported that EC_{50} values for decreasing yield 14 d after germination in a loam soil at 159 mg Cd·kg^{-1} for oats *(Avena sativa)*, 171 mg Cd·kg^{-1} for tomato (*Lycoperscium esculentum,* Bellina RZ), and 33 mg Cd·kg^{-1} for lettuce (*Lactuca sativa,* Ravel RZ). Corresponding NOEC values were 10, 32, and 3.2 mg Cd·kg^{-1}. In a humic sand soil, EC_{50} values were 97, 16, and 136 mg Cd·kg^{-1} for oats, tomatoes, and lettuce respectively, and the corresponding NOEC values were 10, <3.2, and 32 mg Cd·kg^{-1}. Turnips *(Brasica rapa)* grown for 10 d in a sandy loam soil also demonstrated sensitivity to cadmium with an EC_{50} value for yield reduction of 111.5 mg Cd·kg^{-1} (Gunther and Pestemer 1990).

Data on the chronic toxicity (exposure period of >14 d) of cadmium exist for many species of terrestrial plants, including some crop species grown in Canada. Mench et al. (1989) observed a 21% yield reduction after 2 months of growth, measured by above-ground plant dry weight, in corn *(Zea mays)* grown in an acid sandy-clay soil enriched to 5.4 mg Cd·kg^{-1} dry weight soil. The decline was primarily due to a reduction in leaf dry weight, although no visible symptoms of cadmium toxicity had developed. Hassett et al. (1976) presented data on the effects of cadmium on corn root elongation showing a 43% decrease at 25 mg Cd·kg^{-1} while Miller at al. (1977), also studying the effects of cadmium on corn plants, reported that a 2.5 mg Cd·kg^{-1} concentration resulted in a 28% decrease in the dry weight of corn plants shoots.

Bingham et al. (1975) did an extensive study on the effects of cadmium on fourteen (14) different commercial plant species grown in silt loam (pH 7.5-7.8) calculating cadmium concentrations resulting a 25% yield decrement. The most sensitive species were spinach and soybean with EC25 values of 4 mg Cd·kg^{-1}and 5 mg Cd·kg^{-1} nominal concentrations respectively while rice was the most resistent species with an EC25 higher than 640 mg Cd·kg^{-1}. In a similar study, John (1973) reported cadmium uptake by eight food crops and noticed that spinach and lettuce were the most sensitive species at 200 mg Cd·kg^{-1} while oats was the least affected at the same concentration in a silt loam with pH at 5.1. Still in a multiple species study, Miles and Parker (1979a) studied the effects of cadmium on Indiana native plant species. Their results indicate that little bluestem was the most resistent to toxic effects of 30 mg Cd·kg^{-1} on shoot weight while Kentucky bluegrass was the most sensitive at that same concentration. In another study, the same authors (Miles and Parker, 1979b) calculated cadmium concentrations inducing a 25% decrease of shoot and root weight of little bluestem. The resulting concentrations were 27 and 18 mg $Cd \cdot kg^{-1}$ for shoot and root weight respectively.

Cadmium threshold concentrations for wheat (*Triticum aestivum* L.) show increasing sensitivity with decreasing pH. LOEC values affecting shoot dry weight were 1.8, 7.0, 14.0 mg $Cd \cdot kg^{-1}$ for an acidic Cambisol (pH 5.6), a Phaeosem (pH 6.9), and a neutral sandy Hortisol (pH 7.0), respectively (Reber 1989). Wheat dry matter yield was reduced at a cadmium application rate of 12.5 $mg \cdot kg^{-1}$ in a loamy sand soil (Singh et al. 1989). In the same study, the authors determined that the upper critical tissue level of cadmium toxicity was 13.2 $mg \cdot kg^{-1}$ in 45-d-old leaves and 2.3 $mg \cdot kg^{-1}$ in the grain. In a soil with similar pH (8.3), Singh and Rattan (1987) determined that grain and straw yields of wheat *(Triticum aestivum)* were reduced at 38–60 mg DTPA-extractable $Cd \cdot kg^{-1}$ soil. Soybeans *(Glycine max)* grown successively in the same soil showed a decline in grain yield at 1.3–8.2 mg DTPA-extractable $Cd \cdot kg^{-1}$, and straw yield started to decline at 9.9–33.3 mg DTPA-extractable $Cd \cdot kg^{-1}$ soil. Muramoto et al. (1990) presented the result of a study at pH 5.95 on the effects of cadmium on wheat and rice plants. They reported that concentrations of 30, 85 and 1000 mg $Cd \cdot kg^{-1}$ applied to wheat resulted in yield decreases of 30, 85 and 97% respectively while only an 8% yield decrease of rice was measured at 30 mg $Cd \cdot kg^{-1}$ and a 31% decrease at 1000 mg $Cd \cdot kg^{-1}$. Working with wheat and soybean, Haghiri (1973) observed that cadmium toxicity began at the lowest application level of 2.5 mg $Cd \cdot kg^{-1}$ in a silty clay loam with a pH of 6.7.

Khan and Frankland (1984) reported that cadmium inhibited root biomass production for oat, wheat and radish. In this report, the corresponding effects have been evaluated from Khan and Frankland (1984) data as a 25% root biomasss decrease for oat at 10 mg $Cd \cdot kg^{-1}$, and decreases of 61% and 32% for wheat and radish respectively at 50 mg $Cd \cdot kg^{-1}$. In another paper, the same authors calculated the effects concentrations resulting in a 50% root and shoot inhibition of radish using both cadmium oxide and cadmium chloride (Khan and Frankland, 1983). They reported that the oxide compound was less toxic than the chloride one since EC50 values for shoots were 190 and 70 mg $Cd \cdot kg^{-1}$ respectively while for roots, the corresponding values were 170 and 44 in the same order.

Coppola et al. (1988) tested four plant species grown on two soil types. Dwarf beans *(Phaseolus vulgaris)* grown until economic maturity showed dry matter reduction in both soils. Negative cadmium influence started at 4 mg $Cd \cdot kg^{-1}$ in a volcanic soil and at 8 mg $Cd \cdot kg^{-1}$ in a terra rossa. Spinach *(Spinacia olaracea)* harvested at a leaf length of 15–20 cm showed dry matter yield reductions at 4 mg $Cd \cdot kg^{-1}$ in the volcanic soil and 2 mg $Cd \cdot kg^{-1}$ in the terra rossa. No response was observed in dry matter production of radish *(Raphanus sativus)*, harvested when the largest root was about 3 g, in the volcanic soil at any dose. In the terra rossa, a depressive effect on yield was observed at only 16 mg $Cd \cdot kg^{-1}$. Ryegrass *(Lolium perenne)* yield was measured after four successive cuts when the longest leaf blades were 20–25 cm in length. In the volcanic soil, only the 0 mg $Cd \cdot kg^{-1}$ treatment was different from the others; in the terra rossa, yield reduction began at 4 mg $Cd \cdot kg^{-1}$. In a study with rye grass and fescue, Carlson and Rolfe (1979) report that plant growth was reduced in a fertilized soil at cadmium concentrations above 10 mg $Cd \cdot kg^{-1}$ for fescue and above 50 mg $Cd \cdot kg^{-1}$ for rye grass. Miller et al. (1976) reported shoot yield decreases of soybean grown in ten different cadmium treated soils and concluded that cadmium uptake decreased as soil pH and

CEC increased. These authors also concluded that tissue concentrations of 3-5 mg Cd·kg^{-1} generally depressed the growth of soybean.

Environment Canada (1995) evaluated no–observable–effect concentrations (NOEC) for radish and lettuce seedling emergence in an artificial soil treated with cadmium chloride at 99 and 44 mg Cd·kg^{-1} dry soil, respectively. LOEC values reported were 174 mg·kg^{-1} dry soil for a 40% reduction in radish seedling emergence and 102 mg·kg^{-1} dry soil for a 29% reduction in lettuce seedling emergence. EC_{25} and EC_{50} values for the same experiment were reported at 157 and 205 mg·kg^{-1} dry soil, respectively, for radish and 94 and 143 mg·kg^{-1} dry soil for lettuce.

Toxicity data for nonagricultural plants is also available for several tree species. Kelly et al. (1979) grew five species of trees (white pine *[Pinus strobus]*, loblolly pine *[Pinus taeda]*, yellow poplar *[Liriodendron tulipfera]*, yellow birch *[Betula alleghaniensis]*, and choke cherry *[Prunus virginiana]*) in a sandy loam soil. The first adverse effects were observed at 100 mg Cd·kg^{-1} and included a significant reduction in seedling height growth for white pine, loblolly pine, and choke cherry; significant reduction in dry root weight for all species; and significant reduction in dry shoot weight for white pine, choke cherry, and yellow birch. Dixon and Buschena (1988) reported the results of a study on the effects of cadmium on *Pinus banksiana* and *Picea glauca* and concluded that ectomycorrhizal colonization can apparently protect seedlings from cadmium toxicity at low or intermediate concentrations.

Total leaf area of red oak *[Q. rubra]* was significantly reduced at 10 mg Cd·kg^{-1}, and levels above 20 mg·kg^{-1} prevented ectomycorrhizal formation on seedling root systems (Dixon 1988). The first significant growth reduction as measured by total dry weight was not apparent until 50 mg Cd·kg^{-1} (Dixon 1988). The effects of cadmium on root elongation of young beech has been studied over a two years period by Hagemeyer et al. (1993) who reported a 61% decrease at a concentration of 180 μmol Cd·kg^{-1}(20.2 mg Cd·kg^{-1}).

4.3 Terrestrial Invertebrates

Metabolic Fate and Behaviour

Hunter et al. (1987) studied cadmium concentrations in the major taxa of invertebrates inhabiting the soil in the vicinity of a copper/cadmium alloying plant. Cadmium was found in decreasing concentrations in Isopoda, Oligochaeta, Linyphiidae, Collembola, Carabidae, Staphylinidae, Chilopoda, Curculionidae, and Orthoptera. Detritivorous soil macrofauna collected in organic surface soil and plant litter from a refinery site showed accumulation of cadmium of 10–20 times. Herbivorous invertebrates showed body:diet concentration factors of 3 to 5 times for cadmium. In contrast, van Straalen and van Wensem (1986) found no food chain effect in a study of 13 species of small, forest-floor arthropods from a pine forest with a sandy soil. Tissue analysis showed.

Many studies have indicated that uptake and accumulation of cadmium by earthworms occurs in contaminated soils (Hartenstein et al. 1980; Kruse and Barrett 1985; Pietz et al. 1984; Simmers et al. 1983). In a field study, Ma (1982) demonstrated that soil pH and the CEC both affected cadmium uptake in earthworms. A significant negative correlation was found between the concentration factor and soil pH, as lowering of pH leads to increased desorption of metal cations. A second significant negative correlation was found between the concentration factor and soil CEC, indicating the general importance of metal availability rather than the total concentration in soils.

Tolerance to elevated cadmium levels in the environment was reported to occur for species of earthworms (Suzuki et al. 1980), aphids (Crawford et al. 1983), and wood lice (van Capelleveen 1985) and could be attributed to the binding of cadmium by a metalloprotein.

Toxicity

Invertebrate toxicity studies selected for use in soil quality guidelines derivation are presented in Table 8, while additional invertebrate studies that were consulted but not used in guidelines derivation are presented in Table 7.

The principal terrestrial invertebrate used to investigate cadmium toxicity has been the earthworm. Filter paper contact tests involve a standardized procedure, but the results do not reflect the changes in cadmium bioavailability associated with soil properties. Earthworms in filter paper contact tests with 48-h exposure periods typically show less tolerance to contaminants than do soil-based tests. Roberts and Dorough (1984) investigating the effect of cadmium chloride on *Eisenia fetida*, determined an LC_{50} range of 10–100 $\mu g{\cdot}cm^{-2}$. Using the same test and organism, Neuhauser et al. (1986a) reported LC_{50} values for the effects of cadmium acetate, cadmium chloride, cadmium nitrate, and cadmium sulfate of 20, 18, 24, and 26, $\mu g{\cdot}cm^{-2}$, respectively.

In an artificial soil of pH 6.0 and a 14-d exposure period, the LC_{50} for *E. foetida* was 1843 mg $Cd{\cdot}kg^{-1}$ (Neuhauser et al. 1985 and 1986a). Using an identical artificial soil and the same pH, van Gestel et al. (1992) reported that a level of 100 mg $Cd{\cdot}kg^{-1}$ had no influence on the growth of the earthworm species *E. andrei* (no-observed-effect concentration [NOEC]). Cocoon production was significantly reduced at all concentrations tested and therefore corresponding to a NOEC less than 10 mg $Cd{\cdot}kg^{-1}$ dry soil. The NOEC value for both the percent of fertile cocoons and the number of juveniles hatching per fertile cocoon, was 100 mg $Cd{\cdot}kg^{-1}$ dry soil, and the LC_{50} was calculated to be higher than 1000 mg $Cd{\cdot}kg^{-1}$ dry soil (van Gestel et al. 1992). In another paper, van Gestel et al. (1991) reported that growth of *E. andrei* was not affected by concentrations lower than 18 mg $Cd{\cdot}kg^{-1}$ in artificial soil but was reduced by 50% at 33 mg $Cd{\cdot}kg^{-1}$ while they evaluated the EC_{50} for sexual development to be 27 mg $Cd{\cdot}kg^{-1}$. In that paper, the authors also report that a concentration of 253 mg $Cd{\cdot}kg^{-1}$ killed 50% of the population of *E. andrei* (van Gestel at al., 1991). Crommentuijn et al. (1993) reported LC_{50} and EC_{50} values on *Folsomia candida* in artificial soil concluding that reproduction and growth processes were retarded but reached eventually the control level. Depending on the exposure period, the LC_{50} values were between 778 and 917 mg $Cd{\cdot}kg^{-1}$, the EC_{50} on body weight were between 159 and higher than 326 mg $Cd{\cdot}kg^{-1}$ while the EC_{50} on the number of offsprings were evaluated between 376 and 807 mg $Cd{\cdot}kg^{-1}$ (Crommentuijn et al., 1993). Also working with artificial soil, Spurgeon et al. (1994) evaluated a NOEC and an LC_{50} higher than 300 mg Cd·kg^{-1} for *E. fetida* while reporting that cocoon production had a NOEC of 39.2 mg Cd·kg^{-1} and was decreased by 50 % at 46.3 mg Cd·kg^{-1}.

Using a mixture of sand-sized particles from the C horizon of a coniferous forest soil and well-decomposed cattle dung, Bengtsson et al. (1986) reported that cocoon production by the earthworm *Dendrobaena rubida* was significantly diminished at pH 4.5 with a cadmium nitrate concentration of 100 mg Cd·kg^{-1} soil. At that concentration, cocoons produced were often aberrantly coloured and occasionally abnormally shaped. At pH 4.5 and a concentration of 10 mg Cd·kg^{-1}, cocoon production was not significantly different from the control, while at pH 5.5, a significant increase in cocoon production was reported. The same concentration at pH 6.5 had a further positive effect on cocoon production.

Malecki et al. (1982) determined lowest-observed-effect concentration (LOEC) values for growth and reproduction of *E. fetida* exposed to six different cadmium compounds. LOEC values for weight reduction, reported as milligrams of cadmium per kilogram dry weight of mixture, were 100 for cadmium acetate, 40 000 for cadmium carbonate, 100 for cadmium chloride, 500 for cadmium nitrate 500 for cadmium oxide, and 50 for cadmium sulfate. LOEC values for reproductive ability measured as cocoon production were 25 for cadmium acetate, 20 000 for cadmium carbonate, 75 for cadmium chloride; 100 for cadmium nitrate 50 for cadmium oxide, and 100 for cadmium sulfate. The carbonate form of cadmium showed much lower toxicity than was demonstrated by any of the other compounds and was attributed to the relatively insoluble nature of the carbonate form. Results also indicate that the reproductive potential of earthworms is likely to be affected before growth. In the same study, Malecki et al. (1982) carried out an experiment on the long-term (20 weeks) effects on reproduction of the same earthworm species with larger and greater quantities of screened soil and manure. Only cadmium acetate was tested and the metal concentrations in the mixture were reduced to ensure survival of the worms and permit evaluation of cocoon production. The LOEC for reproduction, at 50 mg Cd·kg^{-1} dry weight of mixture, was similar to that found in the short-term study.

In a sandy soil (pH 7.0) and an artificial soil (pH 7.0), *tests on E. foetida* yielded LC_{50} values higher than 1000 mg Cd·kg^{-1} dw (van Gestel and van Dis 1988). For both soils, 5% mortality was observed at 1000 mg Cd·kg^{-1}. A second sandy soil of identical composition, but with a pH of 4.1, produced an LC_{50} range between 320 and 560 mg Cd·kg^{-1} (van Gestel and van Dis 1988). Ma (1982) reported that a concentration of 150-mg Cd·kg^{-1} resulted in 3% mortality for *Lumbricus rubellus*, while at 1000 mg Cd·kg^{-1}, 100% mortality was observed.

Environment Canada (1995) reported the effects of cadmium chloride on *E. fetida* in an artificial soil. After 14 d of exposure, no effect on survival (NOEC) was observed at 430 mg Cd·kg^{-1} dry soil. The LOEC, which resulted in 46% mortality, was 1033 mg Cd·kg^{-1} dry soil. Cadmium concentrations at the LC_{25} and LC_{50} levels were 700 and 1100 mg·kg^{-1} dry soil, respectively.

Nonsoil tests by van Straalen et al. (1989), in which the collembolan *(Orchesella cincta)* and oribatid mite *(Platynothrus peltifer)* were exposed to various dietary levels of cadmium in their food source, produced NOEC values for growth of *O. cincta* and for reproduction of *P. peltifer* of 4.7 mg·kg^{-1}

and 2.9 mg·kg^{-1}, respectively. LC_{50} values for dietary exposure were calculated at 179 mg·kg^{-1} after 61 days for *O. cincta* and 357 mg·kg^{-1} for *P. peltifer* after 84 days of exposure.

A 30-d growth experiment with garden snails *(Helix aspersa)* in quartz sand showed that food consumption declined with each increase in cadmium concentration from 0 to 1 000 mg·kg^{-1}, but mortality at any level was rare. However, the LOEC for reduced shell growth and reproductive activity was observed at 25 mg·kg^{-1} (Russell et al. 1981).

Schmidt et al. (1991) reported that hatching success, growth rate (as measured by the weight of adults), and life span of grasshoppers *(Aiolopus thalassinus)* were significantly reduced at concentrations as low as 2 mg Cd·kg^{-1}. In the same study, adverse effects on ovideposition (i.e., fecundity) were observed at 10 mg Cd·kg^{-1} soil.

4.4 Mammals and Birds

Metabolic Fate and Behaviour

Under most circumstances, dietary exposure to cadmium is probably the most important route. Upon ingestion, the absorption of cadmium is influenced by many factors including dose, age, diet, and the presence of other substances, such as calcium (EPA 1988). In animal studies, absorption of cadmium nitrate or cadmium chloride ranged from 0.5% to 3% of the amount ingested (Health and Welfare Canada 1978).

After being absorbed, cadmium is distributed throughout the body and accumulates primarily in the liver and renal cortex. Numerous studies on rats (Weigel et al. 1987), livestock (Frank et al. 1986), terrestrial wildlife (Crete et al. 1989; Glooschenko et al. 1988; Neuhauser et al. 1986b), and humans (Health and Welfare Canada 1978) have indicated that cadmium accumulates in the liver and kidneys of many animals.

Animals have a limited capability to eliminate assimilated cadmium. In humans, the half-life for elimination has been estimated to be between 10 and 33 years (EPA 1988). Therefore, the majority of cadmium that is absorbed by animals is likely to be retained in the body, with concentrations of cadmium in tissues increasing over time. Urine and feces appear to be the most important routes of excretion for cadmium (Health and Welfare Canada 1978).

Toxicity

Mammals and birds toxicity studies selected for use in soil quality guidelines derivation are presented in Table 11, while additional mammals and bird studies that were consulted but not used in guidelines derivation are presented in Table 9 and 10 respectively.

Short-term exposure to cadmium has been associated with a wide range of sublethal adverse effects on mammalian receptors. For example, acute gastroenteritis has been reported in humans following dietary exposure to doses as low as 0.25–0.50 mg $Cd \cdot kg^{-1}$ body weight (BW) (Health and Welfare Canada 1978). The symptoms of cadmium toxicity following acute exposure include nausea, vomiting, diarrhea, muscular cramps, and salivation (EPA 1988). Sensory disturbances, liver injury, and convulsions may be evident following severe intoxications with cadmium. Shock, renal failure, and cardiopulmonary depression are common symptoms following administration of lethal doses of cadmium (EPA 1988).

Data on rats indicate that the acute oral toxicity of cadmium is compound-specific. Lethal oral doses (LD_{50}) of cadmium in rats range from 16 $mg \cdot kg^{-1}$ BW for cadmium cyanide to >5 000 $mg \cdot kg^{-1}$ BW for cadmium sulphide (CEC 1978). In adult mice, short-term (96-h) oral exposure to cadmium chloride resulted in an LD_{50} of 95.5 $mg \cdot kg^{-1}$ BW (Baer and Benson 1987). Pretreatment of test organisms with sublethal levels of cadmium increased their tolerance to subsequent exposure to higher levels of cadmium (i.e., greater than the 96-h LD_{50}). While the acute oral dose of cadmium in humans has not been established, it has been estimated to be in the order of 5–500 $mg \cdot kg^{-1}$ BW (EPA 1988).

A wide variety of adverse effects have been observed in mammals exposed to cadmium for extended periods of time. Adverse effects on the nervous system, kidney, liver, bones, the hematopoietic system, the cardiovascular system, and the immune system, as well as growth, reproduction, and development, have been observed following chronic, low level oral exposure to cadmium (EPA 1988). In addition, long-term exposure to higher doses of cadmium have been associated with teratogenicity, mutagenicity, and carcinogenicity (WHO 1984b).

Renal dysfunction appears to be a relatively sensitive indicator of cadmium toxicity, and proteinuria was evident in rats exposed to cadmium at doses as low as 2.15 $mg \cdot kg^{-1}$ $BW \cdot d^{-1}$ in drinking water (Kotsonis and Klassen, 1978). Similarly, renal dysfunction was observed at even lower doses (0.714 mg $Cd \cdot kg^{-1}$ $BW \cdot d^{-1}$) when cadmium, as cadmium chloride, was administered by subcutaneous injection (Tohyama et al. 1987). Primates may be somewhat less sensitive to the toxic effects of cadmium, as only mild renal dysfunction was observed in rhesus monkeys exposed to 5 mg $Cd \cdot kg^{-1}$ $BW \cdot d^{-1}$ in their diet for a period of 9 years. No effects on renal function were observed in crab-eating monkeys exposed to the same dose for 6 years (Kawashima et al. 1988).

The effects of cadmium on growth rate have been investigated in a number of studies. Decker et al. (1958) reported that, after 90 days of exposure to 3.04 mg $Cd \cdot kg^{-1}$ $BW \cdot d^{-1}$, rats developed anemia and did not gain weight normally. Similar results were obtained by Baranski and Sitarek (1987) who found growth impairment of female rats exposed to 2.86 mg $Cd \cdot kg^{-1}$ $BW \cdot d^{-1}$ for 98 d. In contrast, Weber and Reid (1969) reported that effects on the growth of mice occurred only at much higher doses (170 mg $Cd \cdot kg^{-1}$ $BW \cdot d^{-1}$). Weigel et al. (1987) found that a 14 d exposure to resulted in a reduction of food intake by male Wistar rats. At 0.055 mg $Cd \cdot kg^{-1}$ $BW \cdot day^{-1}$, a reduction in the rate of food consumption was evident after a 35-d exposure period. Within 56 d, the effects on food consumption had translated into reduced growth rates. The no-adverse-effect dose (NOED) in this study was evaluated at 0.014 mg $Cd \cdot kg^{-1}$ $BW \cdot d^{-1}$ (Weigel et al. 1987).

Reproductive and developmental effects have been reported in rats exposed orally to cadmium. The number of fetal implants and the number of live fetuses were significantly reduced at 10 mg $Cd{\cdot}kg^{-1}$ $BW{\cdot}d^{-1}$ (Sutou et al. 1980). In addition, fetal body weights were also reduced at this dosage. Effects on the duration of the estrous cycle have also been observed in female rats fed 28.6 mg $Cd{\cdot}kg^{-1}$ $BW{\cdot}d^{-1}$ for 56 and 98 d (Baranski and Sitarek 1987).

White et al. (1978) administered cadmium to mallard ducks in their food for up to 90 d. Slight alterations in renal morphology, specifically interstitial nephritis, were evident within 30 d at very low doses (0.15 mg $Cd{\cdot}kg^{-1}$ $BW{\cdot}d^{-1}$). After 90 d of exposure to 1.45 and 19.1 mg $Cd{\cdot}kg^{-1}$ $BW{\cdot}d^{-1}$, moderate to severe tubular degeneration and tubular necrosis were also observed. No effects on growth were observed at the highest dose administered. These results were supported by Rao et al. (1990), who observed an increased incidence of lesions and other alterations in renal morphology in Peking ducks administered 7.6 mg $Cd{\cdot}kg^{-1}$ $BW{\cdot}d^{-1}$ in their food.

Only a few studies on the toxicity of cadmium to livestock and wildlife (exception made for rats and mice) were available. However, they provided interesting information on the effects of cadmium even though these studies were done in the 1960s and 1970s. Lynch et al. (1976) noted a 22% decrease of body weight gain as well as a 25% decrease in survival time of calves fed 15 mg $Cd{\cdot}kg^{-1}$ BW three times a week. Also working with calves, Powell et al. (1964) reported that diets between 40 and 160 mg $Cd{\cdot}kg^{-1}$ provoked few clinical symptoms while a 2560 mg $Cd{\cdot}kg^{1}$ diet killed all the calves in a period of 2 to 8 weeks. At 160 mg $Cd{\cdot}kg^{-1}$ diet, weight gain was inhibited by 30% while a 640 mg $Cd{\cdot}kg^{-1}$ diet resulted in a 65% reduction of body weight when compared to controls.

Pond et al. (1966) presented the results of a study on pigs which can be used to calculate an 87% decrease in the average daily weight gain at a 95 mg $Cd{\cdot}kg^{-1}$ diet concentration. The results of a study by Cousins et al. (1973) on cadmium toxicity to growing swine can be used to evaluate 69% and 96% decreases of body weight gain at 450 and 1350 mg $Cd{\cdot}kg^{-1}$ diet, respectively. Lambs seem to be particularly affected by cadmium contamination as reported by Doyle et al. (1974) who noticed that 30 and 60 mg $Cd{\cdot}kg^{-1}$ diets reduced significantly growth rate and feed intake. Using their results, a 21% decrease on body weight gain can be calculated at 60 mg $Cd{\cdot}kg^{-1}$ diet.

The effects of cadmium on chicks were studied by Freeland and Cousins (1973) who reported 350 and 150 fold increases of cadmium content in the liver and kidney respectively when exposed to a treatment of 75 mg $Cd{\cdot}kg^{-1}$ diet. At this concentration, a 36% decrease in body weight gain can be calculated using reported data (Freeland and Cousins, 1973). Richardson et al. (1974) worked with quails in order to evaluate the pathological changes provoked by 75 mg $Cd{\cdot}kg^{-1}$ diet and reported data indicating a 15% body weight decrease at that dietary level. Spivey Fox et al. (1971), also studied the effects of cadmium on quails, but at a younger stage than Richardson et al. (1974), and reported data corresponding to a 30% body weight decrease at 75 mg $Cd{\cdot}kg^{-1}$ diet.

Effects on reproduction have also been observed in birds exposed to cadmium for protracted periods. White et al. (1978) reported severe changes in the morphology of the testes of mallard ducks exposed to 19.1 mg $Cd{\cdot}kg^{-1}$ $BW{\cdot}d^{-1}$ for 90 d. Egg production of mallard hens was also impaired at this dosage

(White and Finley 1978). Similarly, the production of eggs was reduced in domestic chickens exposed to concentrations higher than 3 mg $Cd \cdot kg^{-1}$ $BW \cdot d^{-1}$ (Leach et al. 1979; Sell 1975).

4.5 Bioconcentration

The bioconcentration factor (BCF) is the ratio of a substance's concentration in an organism to its concentration in ambient water, soil, sediment, or air (Connell 1989). Most studies in the scientific literature do not directly state BCFs, but report concentrations in organisms and in soil separately. From a review of these reported concentrations in a variety of earthworm species, plants, and soil types, a soil-to-invertebrate BCF of 8.30 has been calculated (Environment Canada 1994a). In another report (Environment Canada 1994b), soil-to-plants BCFs have been calculated for different plant tissues and gave BCFs values of 1.81, 1.07 and 15.22 for leaves, shoots, and roots respectively using the results of many studies (Bache and Lisk 1990, Burton and Morgan 1984, Kelly et al. 1979, Kim et al. 1988, and Wadge and Hutton 1986).

However, using the geometric mean of all the BCFs for those plant tissues, an overall BCF value of 2.65 can be calculated. Therefore, the value of the soil-to-plant BCF for cadmium used in the derivation of the soil and food ingestion guideline in this document will be 2.65 (Environment Canada 1994b).

5. DERIVATION OF ENVIRONMENTAL SOIL QUALITY GUIDELINES

5.1 Introduction

Canadian soil quality guidelines are designed to protect four different land uses: agricultural, residential/parkland, commercial and industrial. The Canadian soil quality guidelines for cadmium are based on the procedures described in CCME (1996).

All data selected for use in the following derivations have been screened for ecological relevance and are presented in Tables 5, 8 and 11. Studies that have been consulted but not used in guideline derivation are presented in Tables 4, 6, 7, 9, and 10. Studies were excluded from use because of one or more of the following reasons:

- soil pH was not recorded;
- soil pH was below 4 (as this is considered outside the normal pH range of most soils in Canada);
- no indication on texture was provided;
- inappropriate statistical analysis was used;
- test was not conducted using soil or artificial soil;
- test soil was amended with sewage sludge or a mixture of toxicants;
- test did not used controls.

LOEC and EC data used in the following derivations were considered to be statistically significant according to the study from which the data were taken.

According to Section 7.5.2.2 of the protocol (CCME 1996), the geometric mean should be used when multiple data are available for the same endpoint with the same species. For the cadmium data, the geometric mean has been applied to the effective concentrations for reduced wheat yield from Reber (1989), the NOEC values for cocoon production by earthworms from van Gestel et al. (1991) and Spurgeon et al. (1994), EC50 values for reduced growth of tomato, lettuce and oats from Adema and Henzen (1989), EC50 values for reduction of radish shoot growth and root growth from Khan and Frankland (1984), EC50 values for the reduction in the number of offspring and body weight and LC50 values for collembolan from Crommentuijn et al. (1993), LC50 values for earthworms from van Gestel et al. (1991), Environment Canada (1995) and Neuhauser et al. (1985), EC50 and EC30 values for reduced soybean shoot yield from Miller et al. (1976). By taking the geometric means, the total number of invertebrate and plant toxicity data points has been reduced from 140 to 122.

5.2 Soil Quality Guidelines for Agricultural and Residential/Parkland Land Uses

5.2.1 Soil Quality Guideline for Soil Contact (SQG_{SC})

The derivation of the soil quality guideline for soil contact (SQG_{SC}) is based on toxicological data for vascular plants and soil invertebrates. The toxicological data for plants and invertebrates selected according to CCME (1996) are presented in Table 8. There were sufficient toxicological data to use the preferred weight of evidence method for guideline derivation.

The threshold effects concentration (TEC) was calculated as follows.

$$TEC = NPER / UF$$

where,

TEC = threshold effects concentration ($mg{\cdot}kg^{-1}$ soil)
NPER = no potential effects range (25th percentile of effects and no effects data distribution) ($mg{\cdot}kg^{-1}$ soil)
UF = uncertainty factor (if needed); an uncertainty factor of 2 was applied because of evidence for the potential for cadmium to bioaccumulate (see section 4.5).

Out of a total of 122 data points, the 25th percentile corresponds to the 30th datum point of 20 $mg{\cdot}kg^{-1}$ soil from the Dixon and Buschena (1988) study on the reduction of shoot dry weight of Jack pine (*Pinus Banksiana*).

Thus,

TEC = 20 / 2 = 10 $mg{\cdot}kg^{-1}$ soil

Nutrient and Energy Cycling Check

The nutrient and energy cycling check was calculated using the selected microbial processes data presented in Table 5. Nitrification and nitrogen fixation data are considered to be primary data, whereas nitrogen mineralisation, denitrification and carbon cycling data are considered secondary data. LOEC data, as reported by the author(s), are used directly, while effective concentration (EC) data producing >15 and < 40% effects in primary data (i.e. EC_{15} to EC_{40}) and >15 and < 25% effects in secondary data (i.e. EC_{15} to EC_{25}) are interpreted as LOEC values. Only secondary data were available and the check was carried out using a modified LOEC method whereby the geometric mean of available LOECs is calculated as the nutrient and energy cycling check.

The nutrient and energy cycling check (NECC) was calculated as follows.

$$NECC = (LOEC_1 \bullet LOEC_2 \bullet LOEC_3 \bullet \ldots \bullet LOEC_n)^{1/n}$$

where,
NECC = nutrient and energy cycling check ($mg \cdot kg^{-1}$ soil)
LOEC = lowest observed effects concentration ($mg \cdot kg^{-1}$ soil)
n = number of available LOECs

Thus,
NECC = $(5 \bullet 5 \bullet 2.6 \bullet 2.7 \bullet 7.8 \bullet 400 \bullet 1000)^{1/7}$ = 18 $mg \cdot kg^{-1}$ soil

Since TEC (10 $mg \cdot kg^{-1}$ soil) is lower than the NECC (18 $mg \cdot kg^{-1}$ soil), the TEC is considered to be protective of microbial nutrient and energy cycling processes and is adopted directly as the SQG_{SC} for agricultural and residential/parkland land uses.

5.2.2 Soil Quality Guideline for Soil and Food Ingestion (SQG_I)

The soil quality guideline for ingestion applies only to agricultural land use.

Calculation of the SQG_I is based on the lowest–observed–adverse–effects level (LOAEL) taken from the mammalian and avian toxicological data listed in Table 11. The LOAEL indicating the species most threatened was 4.56 mg $Cd \cdot kg^{-1}$ $bw \cdot d^{-1}$, which resulted in clinical toxicological signs and lesions in lambs (Doyle et al. 1974).

The LOAEL is used to calculate the daily–threshold–effects dose (DTED) according to the equation:

$$DTED = \text{lowest LOAEL} / UF$$

where,
DTED = daily–threshold–effects dose ($mg \cdot kg^{-1}$ $bw \cdot d^{-1}$)
LOAEL = lowest observed adverse effects level ($mg \cdot kg^{-1}$ $bw \cdot d^{-1}$)

UF = uncertainty factor; an uncertainty factor of 2 is applied as the LOAEL is considered to be biologically significant and extrapolation below this level is required. An additional uncertainty factor of 5 is applied as the results are from a relatively short term study compared to the life span of sheep (about 10 years) and as there are indications that cadmium accumulates in the liver and kidneys of animals.

Thus,
DTED = $4.56 / (2 \times 5) = 0.456$ $mg \cdot kg^{-1}$ $bw \cdot d^{-1}$

An animal may be exposed to a contaminant by more than one route. Total exposure comes from a combination of contaminated food, direct soil ingestion, dermal contact, contaminated drinking water and inhalation of air and dust. Exposure from all of these routes should not exceed the DTED. Assuming that drinking water, dermal contact and inhalation account for 25% of the total exposure (CCME 1996), the remaining 75% of exposure is attributed to the ingestion of food and soil. It follows then, that exposure from soil and food ingestion should not exceed 75% of the DTED:

$$\text{exposure from direct soil ingestion} + \text{exposure from food ingestion} = 0.75 \bullet \text{DTED}$$

Exposure from Direct Soil Ingestion

To estimate the exposure of an animal from direct soil ingestion, the rate of soil ingestion must be calculated. The ingestion rate of soil and forage together is referred to as the dry matter intake rate (DMIR). To estimate the rate of soil ingested directly, the percentage of the DMIR attributed to soil ingestion must be isolated. In most soil-based exposure studies, the proportion of soil ingested (PSI) is reported with the DMIR. The animal's soil ingestion rate is calculated as a proportion of the DMIR according to the equation:

$$\text{SIR} = \text{DMIR} \bullet \text{PSI}$$

where,
SIR = the soil ingestion rate (kg dw $soil \cdot d^{-1}$)
DMIR = geometric mean of available dry matter intake rates ($kg \cdot d^{-1}$); estimated to be 1.6 $kg \cdot d^{-1}$ (P. Warrington 1995, British Columbia Ministry of the Environment, Lands and Parks, pers. com.).
PSI = geometric mean of available soil ingestion proportions reported with DMIR. As no information is available on the PSI for the species used, a default value of 0.083 (McMurter 1993) was used for the above equation.

Thus,
SIR = $1.6 \bullet 0.083 = 0.1328$ kg dw $soil \cdot d^{-1}$

The SIR can then be combined with the bioavailability factor (BF), body weight (BW) and a concentration of the contaminant in the soil (SQG_I) to represent the exposure from soil ingestion.

The soil concentration at this point is unknown, but it should not provide for greater than 75% of the DTED when combined with the exposure calculated for food ingestion.

$$\text{exposure from soil ingestion} = SIR \bullet BF \bullet SQG_I / BW$$

where,

SIR = soil ingestion rate (kg dw soil·d^{-1})

BF = bioavailability factor; because of lack of specific information on the bioavailability of cadmium from ingested soil for livestock and terrestrial wildlife, a BF of 1 is assumed (CCME 1996).

SQG_I = concentration of the contaminant in soil that will not result in >75% DTED (mg·kg^{-1} soil)

BW = mean body weight (kg); the mean body weight of lambs was determined to be 45 kg (P. Warrington 1995, British Columbia Ministry of the Environment, Lands and Parks, pers. com.).

Exposure from Food Ingestion

Similar to SIR, the food ingestion rate (FIR) for livestock and wildlife, is expressed as a portion of DMIR. The FIR is the remaining proportion of the DMIR minus soil ingestion rate. The FIR is calculated as:

$$FIR = DMIR - SIR$$

where,

FIR = food ingestion rate (kg dw food·d^{-1})

DMIR = geometric mean of dry matter intake rates (kg dw food·d^{-1})

SIR = soil ingestion rate (kg dw soil·d^{-1})

Thus,

FIR = 1.6 - 0.1328 = 1.4672 kg dw food·d^{-1}

The FIR can then be combined with the bioconcentration factor (BCF), BW and the SQG_I to express the exposure from food ingestion.

$$\text{exposure from food ingestion} = FIR \bullet BCF \bullet SQG_I / BW$$

where,

FIR = food ingestion rate (kg dw food·d^{-1})

BCF = bioconcentration factor; calculated from the data on plant accumulation of cadmium to be 2.65 (Environment Canada 1994b).

SQG_I = concentration of the contaminant in soil that will not result in greater than 75% DTED (mg·kg^{-1} soil).

BW = mean body weight (kg); the mean body weight of lambs was determined to be 45 kg (P. Warrington 1995, British COlumbia Ministry of the Environment, Lands and Parks, pers. com.).

Exposure from Direct Soil Ingestion and Food Ingestion

The equations for exposure from soil ingestion and exposure from food ingestion can be combined and rearranged to solve for the SQG_I:

$$(SIR \bullet BF \bullet SQG_I / BW) + (FIR \bullet BCF \bullet SQG_I / BW) = 0.75 \bullet DTED$$

Thus,

SQG_I = (0.75 DTED • BW) / (SIR • BF + FIR • BCF)

SQG_I = (0.75 • 0.456 • 45) / (0.1328 • 1 + 1.4672 • 2.65)

SQG_I = 3.8 mg Cd·kg^{-1} soil

5.3 Soil Quality Guidelines for Commercial and Industrial Land Uses

5.3.1 Soil Quality Guidelines for Soil Contact (SQG_{SC})

The derivation of the SQG_{SC} is also based on toxicological data for vascular plants and soil invertebrates presented in Table 8. However, for commercial and industrial land uses, only the effects data are used and uncertainty factors are not applied. There were sufficient toxicological data to use the preferred weight of evidence method for guideline derivation.

The effects concentration low (ECL) is calculated as:

$$ECL = ERL$$

where,

ECL = effects concentration low (mg·kg^{-1}soil)

ERL = effects range low (25th percentile of effects data distribution) (mg·kg^{-1})

Out of a total of 104 data points, the 25th percentile corresponds to the 26th datum point of 27 mg·kg^{-1} soil from the van Gestel et al. (1991) study on the sexual development of earthworms.

Thus,

ECL = 27 mg·kg^{-1} soil

Nutrient and Energy Cycling Check

The nutrient and energy cycling check was calculated using the selected microbial processes data presented in Table 5. Nitrification and nitrogen fixation data are considered to be primary data, whereas nitrogen mineralisation, denitrification and carbon cycling data are considered secondary data. LOEC data, as reported by the author(s), are used directly while effective concentration (EC) data producing >15 and < 50% effects in primary data (i.e. EC_{15} to EC_{50}) and >15 and <35% effects in secondary data (i.e. EC_{15} to EC_{35}) are interpreted as LOEC values. Only secondary data were available and the check was carried out using a modified LOEC method whereby the geometric mean of available LOECs is calculated as the nutrient and energy cycling check.

The nutrient and energy cycling check (NECC) was calculated as follows.

$$NECC = (LOEC_1 \bullet LOEC_2 \bullet LOEC_3 \ldots LOEC_n)^{1/n}$$

where,
NECC = nutrient and energy cycling check ($mg \cdot kg^{-1}$ soil)
LOEC = lowest observed effects concentration ($mg \cdot kg^{-1}$ soil)
n = number of available LOECs

Thus,

$$NECC = (5 \bullet 5 \bullet 5 \bullet 2.6 \bullet 2.7 \bullet 7.8 \bullet 400 \bullet 1000 \bullet 250 \bullet 562 \bullet 562 \bullet 562 \bullet 562 \bullet 562 \bullet 8000)^{1/15}$$
$$= 92\ (mg \cdot kg^{-1}\ soil)$$

Since ECL (27 $mg \cdot kg^{-1}$ soil) is lower than the NECC (92 $mg \cdot kg^{-1}$ soil), the ECL is considered to be protective of microbial nutrient and energy cycling processes and is adopted directly as the SQG_{SC} for commercial and industrial land uses.

5.4 Derivation of Final Environmental Soil Quality Guidelines (SQG_E)

The following eenvironmental soil quality guidelines are optimized for soils within the pH range of 4.0 to 8.1. The toxicological studies upon which these guidelines are based were conducted within this pH range. A summary of all the derived soil quality guidelines is presented in Table 12.

Agricultural Land Use

The lower value from the two procedures (SQG_{SC} and SQG_I) is selected as the final environmental soil quality guideline (SQG_E) for agricultural lands. The lower of the two procedures is the SQG_{SC}. Therefore, the final SQG_E for agricultural land use is 3.8 $mg \cdot kg^{-1}$ soil.

Residential/Parkland Land Use

The SQG_{SC} of 10 $mg \cdot kg^{-1}$ soil is the final SQG_E for residential/parkland land use.

Commercial and Industrial land uses

The SQG_{SC} of 27 $mg \cdot kg^{-1}$ soil is the final SQG_E for commercial and industrial land use.

6. DATA GAPS

Sufficient data exist on the toxicity of cadmium to soil ecosystem receptors to derive soil quality guidelines for the three major uses of land (Agricultural, Residential/Parkland, and Commercial/Industrial). Additional data are required, however, to refine our understanding of the fate and effects of cadmium in the environment.

A significant database exists on the fate of cadmium in soils and other environmental media. However, much of this information is inconclusive and these data are frequently contradictory. It is likely that a variety of factors, such as pH, moisture content, clay content, and organic matter content, act together to influence the fate of cadmium in soils. Additional information is required to fully understand the importance of each of these factors in determining the fate of anthropogenic cadmium in soils. These data will also contribute to our understanding of the bioavailability of cadmium in various soil types.

A substantial database exists on the toxicity of cadmium to terrestrial plants. However, despite the extent of the data set, insufficient information currently exists to reliably predict the bioavailability of cadmium in Canadian soils. Therefore, additional information is required to evaluate the influence of pH, organic matter content, clay content, and other factors on the toxicity of cadmium in soil. In the future, the soil quality guidelines should be refined to incorporate the factors that have been demonstrated to influence the toxicity of cadmium. Furthermore, field validation of the recommended guidelines will be required to confirm that the uptake and toxicity of cadmium, as reported in the literature, are representative of conditions in Canadian soils.

Cadmium is a naturally occurring substance that may be toxic at concentrations at or below regional background levels. Therefore, additional information is required on regional background levels of cadmium in Canadian soils in order to support the derivation of realistic soil quality objectives for cadmium at sites across the country.

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TABLES

Table 1. Physical and chemical properties of cadmium and its common salts.

Property	*Cadmium*	Cadmium chloride	Cadmium oxide	Cadmium sulfide	Cadmium carbonate	Cadmium acetate
Chemical formula	Cd	$CdCl_2$	CdO	CdS	$CdCO_3$	$Cd(C_2H_3O_2)_2$
Molecular weight	112.40	183.32	128.40	144.47	172.42	230.49
Physical state	Soft bluish white metal	Small white crystals	Colourless, amorphous crystals	Yellow powder	White, amorphous powder	Colourless crystals
Boiling point (°C)	765	960	1559	ND*	ND	ND
Melting point (°C)	320.9	568	900	980	<500	255
Density ($g\ cm^{-3}$)	8.642	4.047	8.15	4.5–4.82	4.258	2.01–2.34
Vapour pressure (mm Hg)	1.4	ND	ND	ND	ND	ND
Solubility ($g \cdot 100\ mL^{-1}$ cold water)	Insoluble	140	Insoluble	0.00013	Insoluble	Very soluble

Source: EPA 1985; Budavari et al. 1989; CRC 1992.
*ND = No data.

Table 2. Cadmium concentrations in Canadian soils.

Location	Sample depth (cm)	Soil type	Concentration (SD*) (mg·kg⁻¹)	Range (mg·kg⁻¹)	Comments	References
CANADA						
Various site	NR**	Topsoils	0.9 (NR)	0.40–1.7	-	Bewers et al. 1987
Various sites	NR	NR	0.07	0.01-0.1	-	NRCC 1979
Prairie region	NR	NR	0.3	<0.2-3.8	-	Garrett 1994
BRITISH COLUMBIA						
Various sites	NR	Topsoils	0.88 (NR)	<0.1–4.67	-	Bewers et al. 1987
Liard River Basin Northern Region	Surface Surface	River bank River/lake bank	0.26 (0.15) 0.38 (0.45)	0.1–0.5 0.1–1.8	-	Sekerak and Mace 1982
Fraser River Valley	NR	Agricultural soils	0.88 (NR)	<0.5–4.67	-	John 1975
Vancouver	<10 15 20 25 >80	NR	10.7 (15.9) 0.42 (0.18) 0.29 (NR) 0.75 (NR) 1.37 (2.85)	0.23–37.2 0.23–0.58 0.08–0.50 0.74–0.76 <0.1–9.38	Near CIL plant	Golder Assoc. Ltd. 1989
Trail	Surface	Surface litter	17.1 (NR) 3.5 (NR)	max = 36 NR	0–10 km from lead-zinc smelter 6–135 km from lead-zinc smelter	John 1975
Trail	Surface	Garden soils	19 (NR) 5 (NR)	NR NR	<4 km from lead-zinc smelter 50 km from lead-zinc smelter	Lynch et al. 1980
Not reported	NR	NR	49 (NR) 1.6 (NR) 0.6 (NR)	7.9–95 NR NR	15 m from battery reclamation smelter stack 30 m from battery reclamation smelter stack 90 m from battery reclamation smelter stack	John 1975

Location	Sample depth (cm)	Soil type	Concentration (SD*) (mg·kg⁻¹)	Range (mg·kg⁻¹)	Comments	References
ALBERTA						
Northwestern region	Surface <20 cm	Agricultural soils	0.3 (NR)	NR		Soon and Abboud 1990
	Subsurface 15 cm below plough layer		0.2 (NR)	<0.1–0.6		
Southeast and central region	A, B, and C horizons	Chernozemic and Luvisolic soils	NR (NR)	0.06–0.53	Background levels	Dudas and Pawluk 1980
MANITOBA						
Flin Flon	Surface	Garden soils	5.19 (NR)	3.2–13	0.3–12.8 km from copper smelter	Pip 1991
Winnipeg	<15	Urban soils	1.09 (0.26)	0.7–1.7	Urban area	Mills and Zwarich 1975
Southwest region	<15	Roadside soils	1.22 (0.08)	1.1–1.3	Ditch	
	<15	Agricultural soils	1.03 (0.08)	1.0–1.2	50 m from road	
			1 (0.06)	0.9–1.1	100 m from road	
	A horizon		0.95 (0.32)	0.4–1.7	Background	
			1.1 (0.32)	0.5–1.7	Background	
ONTARIO						
Various	NR	NR	1.14 (NR)	0.55–1.72		Bewers et al. 1987
		Topsoils	0.97 (NR)	0.1–8.1		
Various	NR	Agricultural soils	0.8 (NR)	NR	Background	Webber and Shamess 1987
Toronto	Surface	Roadside soils	NR (NR)	2–8	<1 m from road	Van Loon et al. 1973
			NR (NR)	<0.5–3	6–15 m from road	
Halton region	<15	Agricultural soils	<0.5 (NR)	<0.5–2.4	Background	Webber and Shamess 1987
			0.95 (NR)	0.19–4.3	Sludge treated	
Oshawa	Surface	NR	0.53–0.73 (0.31–0.43)	NR	6-year-old transmission towers	Jones et al. 1988
			1.34–1.49 (0.31–0.43)	NR	30-year-old transmission towers	

Location	Sample depth (cm)	Soil type	Concentration (SD*) (mg·kg^{-1})	Range (mg·kg^{-1})	Comments	References
Various	15	Agricultural soils	0.56 (0.69)	0.1–8.1	background levels	Frank et al. 1976
		sandy soils				
		loam soils	0.43 (0.029)	0.10-1.80		
		clay soils	0.71 (1.11)	0.12-8.10		
		all soils	0.57 (0.32)	0.12-1.61		
			0.56 (0.69)	0.1-8.1		
Southwestern region	A, B, and C horizons	Agricultural soils	NR (NR)	ND***–1.7		Whitby et al. 1978
QUEBEC						
Rouyn-Noranda	<15	Peat	NR (NR)	54–66	1–3.7 km from smelter	Dumontet et al. 1990
	15–30		NR (NR)	4.2–11	1–3.7 km from smelter	
	<15		NR (NR)	13–19	5–15 km from smelter	
	15–30		NR (NR)	0.7–3.5	5–15 km from smelter	
	<15		NR (NR)	5.5–7.8	25–43 km from smelter	
	15–30		NR (NR)	0.3–2.6	25–43 km from smelter	
NOVA SCOTIA						
Charlo	<15	NR	1.8 (NR)	NR		Sergeant and Westlake 1980
Bathurst			1.6 (NR)	NR		
Tabusintac			1 (NR)	NR		
Belledune			6.7 (6.8)	2–22.2	Vicinity of lead smelter	
North Shore and Annapolis Valley	<15	Agricultural soils	NR (NR)	0.11–0.43	0.1 M HCl extractable	Baker and Matheson 1980

* SD = standard deviation
** NR = not reported.
***ND = not detectable.

Table 3. Existing soil quality criteria, guidelines, and standards for cadmium.

Jurisdiction	Category	Guideline (mg·kg^{-1})	Reference
Canada	Interim assessment criteria	0.5	CCME 1991
	Interim remediation criteria:		
	Agricultural	3	
	Residential/parkland	5	
	Commercial/industrial	20	
British Columbia	Cleanup criteria		Angus Environmental Limited 1991
	Agricultural	1	
	Residential/parkland	5	
	Commercial/industrial	20	
Alberta	Assessment criteria	1	
Ontario	Remediation criteria:		OMEE 1994
	Surface soil:*		
	Potable groundwater situation		
	Agricultural	3	
	Residential/parkland	12	
	Commercial/industrial	12	
	Nonpotable groundwater situation		
	Residential/parkland	12	
	Commercial/industrial	12	
	Subsurface soil:†		
	Potable groundwater situation		
	Residential/parkland	83	
	Commercial/industrial	83	
	Nonpotable groundwater situation		
	Residential/parkland	83	
	Commercial/industrial	83	
Quebec	Agricultural	1.5	Angus Environmental Limited 1991
	Residential/parkland	5	
	Commercial/industrial	20	
California	Hazardous	100	Fitchko 1989
	Extremely hazardous	1000	
New Jersey	Surface soil standard:		DEPE 1992
	Residential	1	
	Nonresidential	100	
United States	Human health/ecological integrity		Fitchko 1989
	Continuous exposure	0.08	
	Short-term exposure	0.3	
Great Britain	Domestic gardens	3	
	Parkland	15	
Greater London Council	Uncontaminated	0–1	
	Slightly contaminated	1–3	
	Contaminated	3–10	
	Heavily contaminated	10–50	
	Unusually heavily contaminated	>50	
The Netherlands	Standard soil		RIVM 1994
	Target value	0.8	
	Intervention value	12	

*Surface soil criteria apply only where soil pH is 5.0–9.0.
†Subsurface soil criteria apply only where pH is 5.0–11.0.

Table 4. Consulted studies on the toxicity of cadmium to soil microbial processes.

Species/process	Effect	Endpoint	Concentration (mg·kg^{-1} dw)	Form of Cadmium (exposure period)	pH	Test substrate	Extraction method	Reference
SOIL MICROORGANISMS								
Bacteria/population	Reduction	EC	10	$CdCl_2$ (8 weeks)	7.5	Black soil, OM 0.8%, clay 55%	Nominal	Naidu and Reddy 1988
Bacteria/population	Reduction	EC	0.1	$CdCl_2$ (20 days)	6.0	Silt loam, 2.1%	Nominal	Zibilske and Wagner 1982
Fungi/population	Reduction	EC	10	$CdCl_2$ (8 weeks)	7.5	Black soil, OM 0.8%, clay 55%	Nominal	Naidu and Reddy 1988
Fungi actinomycetes /population	No effect Reduction	EC	10 50	$CdCl_2$ (8 weeks)	7.5	Black soil, OM 0.8%, clay 55%	Nominal	Naidu and Reddy 1988
Fungi/population	90% reduction	EC	2.9	NR* (6 weeks)	NR	Sand, OM 2%	Nominal	Kobus and Kurek 1990
Cellulolytic microbes /population	30%–100% reduction	EC	2.9					
Ectomycorrhizae on red oak /colonization	18% inhibition 100%inhibition	EC	10 50	$CdCl_2$ (16 weeks)	6	Sandy loam, OM 1.5%	Nominal	Dixon 1988
Ectomycorrhizae on jack pine /colonization	Inhibition	EC	10	$CdCl_2$ (12 weeks)	6	Sandy loam, OM 1.5%	Nominal	Dixon and Buschena 1988
Ectomycorrhizae on white pine/colonization	60% inhibition 86% inhibition	EC	2 5					
Blue–green algae /C_2H_2 production	50% decrease	EC	3	Sewage sludge (60 days)	6.5	Sandy loam, clay 9%	Estimated from EDTA-extractable Cd	Brookes et al. 1986

Species/process	Effect	Endpoint	Concentration (mg·kg^{-1} dw)	Form of Cadmium (exposure period)	pH	Test substrate	Extraction method	Reference
SOIL PROCESSES								
Carbon dioxide evolution	50% reduction	EC	2.9	NR (6 weeks)	NR	Sand, OM 2%	Nominal	Kobus and Kurek 1990
Carbon dioxide evolution	50% reduction	EC	13.5	$CdCl_2$ (3 months)	NR	Silt loam, OC 1.3%	DTPA	Chang and Broadbent 1981
Carbon dioxide evolution	40% reduction	EC	10	$CdCl_2$ (4 weeks)	NR	Forest soil	Nominal	Bond et al. 1976
Dehydrogenase activity	Reduction	EC	50	$CdCl_2$ (8-12 years)	6	Sandy luvisol, OM 0.7%, clay 7%	Aqua regia	Wilke 1991
Nitrification	25% reduction	EC	10	$CdCl_2$ (6 weeks)	7.5	Black soil, OM 0.8%, clay 55%	Nominal	Naidu and Reddy 1988
Nitrification	67% inhibition	EC (a)	5	$CdSO_4$ (10 days)	7.4	5.45% O.C., 34% clay	Nominal	Liang & Tabatabai, 1978
	70% inhibition	EC (a)	5		7.8	3.74% O.C., 30% clay		
	94% inhibition	EC (a)	5		5.8	2.58% O.C., 23% clay		
Nitrification/denitrification	60% reduction	EC	2.9	NR (6 weeks)	NR	Sand, OM 2%	Nominal	Kobus and Kurek 1990
Nitrogen fixation	No effect 80% reduction	EC	2 8	$CdSO_4$ (48 hours)	6.4 6.4	Volcanic, OM 1.2%, clay 7.7%	Nominal	Coppola et al. 1988
Nitrogen fixation	100%inhibition	EC	7.1	$CdSO_4$ (18 months)	6.5	Sandy loam, clay 9%	Aqua regia	Chaudri et al. 1992b
Arylsulphatase activity	Inhibition	EC_{10} EC_{50}	3.4 121	$CdCl_2$ (18 months)	7	Sand, OM 1.6%	Nominal	Haanstra and Doelman 1991
		EC_{10} EC_{50}	3.4 1798		6	Sandy loam,OM 5.7%		
		EC_{10} EC_{50}	6.7 137		7.7	Silty loam, OM 2.4%		
		EC_{10} EC_{50}	28 1016		7.5	Clay, OM 3.2%		

Species/process	Effect	Endpoint	Concentration ($mg \cdot kg^{-1}$ dw)	Form of Cadmium (exposure period)	pH	Test substrate	Extraction method	Reference
ATP activity	Reduction	EC	0.1	$CdCl_2$ (80 days)	6.0	Silt loam, OM 6%	Nominal	Zibilske and Wagner 1982
Phosphatase activity	Inhibition	EC_{10} EC_{50}	16 330	$CdCl_2$ (18 months)	7	Sand, OM 7%	Nominal	Doelman and Haanstra 1989
		EC_{10} EC_{50}	8070 9870		6	Sandy loam, OM 6%		
		EC_{10} EC_{50}	13 230		7.7	Silty loam, OM 7.7%		
		EC_{10} EC_{50}	830 5305		7.5	Clay, OM 5%		

*Not reported.
a: The concentration reported here comes from a single concentration study.

Table 5. Consulted studies on the toxicity of cadmium to terrestrial invertebrates.

Species	Effect	Endpoint	Concentration (SD) (mg·kg^{-1})*	Form of Cadmium (Exposure period)	Soil pH	Test substrate	Extraction method	Reference
Earthworm (*E. foetida*)	Mortality	LC_{50}	10–100 µg· cm^{-2}	$CdCl_2$ (48 hours)	NA	Filter paper contact test	Nominal	Roberts and Dorough 1984
Earthworm (*E. foetida*)	Mortality	LC_{50} LC_{50} LC_{50} LC_{50}	20 µg·cm^{-2} 18 µg·cm^{-2} 24 µg·cm^{-2} 26 µg·cm^{-2}	$Cd(C_2H_3O_2)_2$ $CdCl_2$ $Cd(NO_3)_2$ $CdSO_4$ (48 hours)	NA	Filter paper contact test	Nominal	Neuhauser et al. 1986a
Earthworm (*E. foetida*)	Growth Mortality	LOEC LOEC	1 800–18 000 3 500–35 000	$CdCl_2$ or CdO (-)	NR	Activated sludge	(-)	Hartenstein et al. 1981
Earthworm (*E. foetida*)	Cocoon production Growth (weight reduction)	LOEC LOEC	25 20 000 75 100 50 100 100 40 000 100 500 500 50	$Cd(C_2H_3O_2)_2$ $CdCO_3$ $CdCl_2$ $Cd(NO_3)_2$ CdO $CdSO_4$ (8 weeks) $Cd(C_2H_3O_2)_2$ $CdCO_3$ $CdCl_2$ $Cd(NO_3)_2$ CdO $CdSO_4$ (8 weeks)	NR	Metal and horse manure mixture over screened soil	Nominal	Malecki et al. 1982
Earthworm (*E. foetida*)	Mortality	LC_{50} LC_{50} LC_{50}	>1 000 >1 000 320–560	$CdCl_2$ (14 days)	7 7 4.1	Sandy soil. O.M. 1.7%, % clay 4.3 OECD (1984) artificial soil, O.M. 7.7%, % clay 10.4 Sandy soil, O.M. 1.7%, % clay 4.3	Nominal	van Gestel and van Dis 1988

Species	Effect	Endpoint	Concentration (SD) (mg·kg⁻¹)*	Form of Cadmium (Exposure period)	Soil pH	Test substrate	Extraction method	Reference
Collembolan *(Orchesella cincta)*	Growth Mortality	NOEC LC_{50}	4.7 179	$CdSO_4$ in green algae (61 days)	NR	Plaster of paris	Nominal	van Straalen et al. 1989
Orbatid mite *(Platynothrus peltifer)*	Reproduction Mortality	NOEC LC_{50}	2.9 357	$CdSO_4$ in green algae (84 days)	NR	Purified sand with filter paper cover		
Garden snail *(Helix aspersa)*	Reduced shell growth and reproduction	LOEC	25	$CdCl_2$ in lab-chow (30 days)	NR	Quartz sand	Nominal	Russell et al. 1981
Grasshopper *(Aiolopus thalassinus)*	Adult weight, hatching success Ovideposition	LOEC LOEC	2 10	$CdCl_2$ in diet (2 generations)	NR	Builder's sand	Nominal	Schmidt et al. 1991

* = Except where indicated.
NOEC = No-observed-effect concentration.
LOEC = Lowest-observed-effect concentration. .
EC = Effective concentration..
LC = Lethal concentration.
SD = Standard deviation
NA = Not applicable
NR = Not reported.

Table 6. Consulted studies on the toxicity of cadmium to terrestrial plants.

Species	Effect	Endpoint	Effect concentration	Form of Cadmium (Exposure period)	Soil pH	Test substrate	Extraction Method	Reference
Wheat *(T. aestivum)*	reduced grain and straw yields	LOEC	38–60 μg $Cd \cdot g^{-1}$ soil	$CdSO_4$ (Not reported)	8.3	Typic Ustipsamment rich in illite clay	DPTA extraction	Singh and Rattan 1987
Soybeans *(Glycine max)*	reduced grain yield	LOEC	1.3–8.2 μg $Cd \cdot g^{-1}$ soil					
	reduced straw yield	LOEC	9.9–33.3 μg $Cd \cdot g^{-1}$ soil					
Dwarf beans *(Phaseolus vulgaris)*	reduced dry matter yield	LOEC	4 $mg \cdot kg^{-1}$	$CdSO_4$ (Not reported)	6.4	Volcanic soil, 1.2% humus, 7.7% clay, 16.8% silt	HNO_3 titration at different pH	Coppola et al. 1988
Spinach *(Spinacia olaracea)*		LOEC	4 $mg \cdot kg^{-1}$					
Radish *(R. sativus)*		--	No response					
Ryegrass *(Lolium perenne)*		LOEC	2 $mg \cdot kg^{-1}$					
Dwarf beans *(P. vulgaris)*	reduced dry matter yield	LOEC	8 $mg \cdot kg^{-1}$	$CdSO_4$ (Not reported)	6.6	'Terra rosa' soil, 1.0% humus, 69.3% clay, 20.3% silt	HNO_3 titration at different pH	Coppola et al. 1988
Spinach *(S. olaracea)*		LOEC	2 $mg \cdot kg^{-1}$					
Radish *(R. sativus)*		LOEC	16 $mg \cdot kg^{-1}$					
Ryegrass *(L. perenne)*		LOEC	4 $mg \cdot kg^{-1}$					

Species	Effect	Endpoint	Effect concentration	Form of Cadmium (Exposure period)	Soil pH	Test substrate	Extraction Method	Reference
Red oak *(Quercus rubra)*	reduced total leaf area	LOEC	10 $mg \cdot kg^{-1}$	$CdCl_2$ (16 weeks)	6.0	Sandy loam soil, 6.0% O.M.	-	Dixon 1988
	ectomycorrhizal formation	LOEC	>20 $mg \cdot kg^{-1}$					
	growth reduction	LOEC	50 $mg \cdot kg^{-1}$					

Table 7. Consulted studies on the acute and chronic toxicity of cadmium to mammals.

Species	Effect	Endpoint	Dose ($mg \cdot kg^{-1} BW \cdot d^{-1}$)	Form of Cadmium (Exposure period)	Reference
Swiss-Webster mouse	mortality 80 % mortality - pretreatment at 0 $mg \cdot kg^{-1}$ 50 % mortality - pretreatment at 5 $mg \cdot kg^{-1}$ 20 % mortality - pretreatment at 10 $mg \cdot kg^{-1}$ 100 % mortality - pretreatment at 0 $mg \cdot kg^{-1}$ 70 % mortality - pretreatment at 5 $mg \cdot kg^{-1}$ 30 % mortality - pretreatment at 20 $mg \cdot kg^{-1}$ 0 % mortality - pretreatment at 50 $mg \cdot kg^{-1}$	LD_{50} LD_{80} LD_{50} LD_{20} LD_{100} LD_{70} LD_{30} LD_0	95.5 100 100 100 150 150 150 150	$CdCl_2$ (96 hours)	Baer and Benson 1987
Mouse	Growth rate Growth rate significantly reduced Bone citric acid level Bone citric acid level reduced	NOEC EC NOEC EC	0 170 0 0.255	NR* (-)	Weber and Reid 1969
Rat	mortality	LD_{50} LD_{50}	16 >5000	CdCN CdS (-)	CEC 1978
Rat	No proteinuria induced Proteinuria induced	NOEC EC	0.84 2.15	NR (24 weeks)	Kotsonis and Klassen 1978
Rat	Growth rate Growth rate significantly reduced	NOEC EC	0.375 3.04	NR (-)	Decker et al. 1958
Rat	Reproduction Number of live fetuses reduced Fetal body weight significantly reduced	NOEC EC EC	1 10 10	$CdCl_2$ (6 weeks)	Sutou et al. 1980
Rat	Renal function Excretion of proteins in urine increased	NOEC EC	0 0.714	$CdCl_2$ (single dose)	Tohyama et al. 1987
Wistar rat	Growth rate Growth rate significantly reduced Duration of estrous cycle Duration of estrous cycle increased	NOEC EC NOEC EC	0.29 2.86 2.86 28.6	$CdCl_2$ (14 weeks)	Baranski and Sitarek 1987
Wistar rat	Food intake (14 days) Food intake rate reduced Food intake (35 days) Food intake rate reduced Growth rate (56 days) Growth rate reduced	NOEC EC NOEC EC NOEC EC	0.047 0.126 0.014 0.055 0.014 0.055	CdO (55 days)	Weigel et al. 1987
Sprague-Dawley rat	Liver enzyme function Liver cytochrome c oxidase activity reduced	NOEC EC	0 0.018	$Cd(C_2H_3O_2)_2$ (single dose)	Muller and Stacey 1988
Monkey *(Macaca fascicularis)*	Vitamin D metabolism Renal function	NOEC NOEC	5	$CdCl_2$ (6 years)	Kawashima et al. 1988
Rhesus monkey *(Macaca mulatta)*	Vitamin D metabolism Renal function Mild renal dysfunction	NOEC NOEC EC	5 1.5 5	$CdCl_2$ (9 years)	Kawashima et al. 1988

*NR = not reported.

Table 8. Consulted studies on the acute and chronic toxicity of cadmium to birds.

Species	Effect	Endpoint (a)	Average Dose ($mg\cdot kg^{-1}$ $BW\cdot d^{-1}$)	Form of Cadmium(Exposure period)	Extraction method	Reference
Mallard duck *(Anas platyrhynchos)*	No effect on growth	NOEC	19.1 (est)	$CdCl_2$ (90 days)	Nominal	Eisler 1985; White et al. 1978
Mallard duck *(A. platyrhynchos)*	No effect on renal morphology Slight change in renal morphology Moderate change in renal morphology Severe change in renal morphology No effect on morphology of testes Severe change in morphology of testes	NOEC EC EC EC NOEC EC	0.008 0.15 1.45 19.1 1.45 19.1	$CdCl_2$ (90 days)	Nominal	White et al. 1978
Mallard duck *(A. platyrhynchos)*	Egg production reduced	EC	19.1	$CdCl_2$ (90 days)	Nominal	Eisler 1985; White and Finley 1978
Peking duck	No effect on renal morphology Slight change in renal morphology Low incidence of lesions in kidney Increased incidence of lesions in kidney	NOEC EC EC EC	0 7.6 (est) 0 7.6 (est)	$CdCl_2$ (12 weeks)	Nominal	Rao et al. 1990
Chicken	Egg production reduced	EC	3.84 (est)	NR (-)	(-)	Sell 1975
Chicken	Egg production reduced	EC	3.07 (est)	NR (-)	(-)	Leach et al. 1979

a: The EC endpoints represent the effects concentration as calculated by the CCME from the data presented by the author(s).
†NR = Not reported.

Table 9. Selected plant and invertebrate toxicological studies for cadmium

Species	Effect (a) (% decrease)	Endpoint	Concentration (mg·kg^{-1})	Form of Cd (exposure period)	Soil pH	Test Substrate	Extraction Method	Reference
Oats, *Avena sativa*	weight	NOEC EC_{50}	10 159	$CdCl_2$ (14 days)	7.5	loam: 1.4% O.M., 17.1% silt	nominal	Adema & Henzen, 1989
		NOEC EC_{50}	10 97		5.1	humic sand: 3.7% O.M., 5.8% silt		
Lettuce, *Lactuca sativa*	weight	NOEC EC_{50}	3.2 33		7.5	loam: 1.4% O.M., 17.1% silt		
		NOEC EC_{50}	32 136		5.1	humic sand: 3.7% O.M., 5.8% silt		
Tomato, *Lycopersicum esculentum*	weight	NOEC EC_{50}	32 171		7.5	loam: 1.4% O.M., 17.1% silt		
		NOEC EC_{50}	<3.2 16		5.1	humic sand: 3.7% O.M., 5.8% silt		
Earthworm, *Dendrobaena rubida*	cocoon production (60%)	EC	100	$CdNO_3$ (3 months)	4.5	sand: O. C. 4.5-6.9%	nominal	Bengtsson et al., 1986
Tomato, *L. esculentum*	ripe fruit yield	EC_{25}	160	$CdSO_4$ (from seed)	7.5-7.8	Domino silt loam	nominal	Bingham et al., 1975
Lettuce, *L. sativa*	head yield	EC_{25}	13					
Zucchini squash *Curcurbita pepo*	fruit yield (25%)	EC	160					
Radish, *Raphanus sativus*	tuber yield (25%)	EC	96					
Wheat, *Triticum aestivum*	grain yield (25%)	EC	50					
Field bean, *Phaseolus vulgaris*	dry bean yield (25%)	EC	40					
Corn, *Zea mays*	kernal yield (25%)	EC	18					
Carrot, *Daucus carota*	tuber yield (25%)	EC	20					

Species	Effect (a) (% decrease)	Endpoint	Concentration (mg·kg⁻¹)	Form of Cd (exposure period)	Soil pH	Test Substrate	Extraction Method	Reference
Turnip, *Brassica rapa*	tuber yield (25%)	EC	28					
Cabbage, *Brassica oleracea*	head yield (25%)	EC	170					
Soybean, *Glycine max*	dry bean yield (25%)	EC	5					
Rice, *Oryza saliva*	grain yield (25%)	EC	>640					
Curlycress, *Lepidium salivum*	shoot yield (25%)	EC	8					
Spinach, *Spinacia oleracea*	shoot yield (25%)	EC	4					
Rye, *Lolium perenne* Fescue, *Festuca rubra*	growth (26%) growth (27%)	EC EC	100 50	$CdCl_2$ (10 days) (20 days)	5.9	silt loam	nominal	Carlson & Rolfe, 1979
Collenbolan, *Folsomia candida*	body weight	EC_{50} EC_{50}	541 566	$CdCl_2$ (30 days) (26 days)	6.0	Artificial soil (OECD, 1984)	HCl-HNO_3 digestion	Crommentuijn et al,. 1993
	survival	LC_{50} LC_{50} LC_{50}	778 822 893	(23 days) (26 days) (30 days)				
	number of offsprings	EC_{50} EC_{50} EC_{50}	159 204 227	(23 days) (26 days) (30 days)				
	body weight	EC_{50}	376	(23 days)				
Pinus Banksiana	shoot dry weight (13%) root dry weight (51%)	EC EC	20 20	$CdCl_2$ (12 weeks)	6.0	sandy loam	nominal	Dixon & Buschena, 1988
Picea glauca	shoot dry weight (35%) root dry weight (45%)	EC EC	20 20					
Red oak *Quercus rubra*	dry weight (27%)	EC	20	$CdCl_2$ (8 weeks)	6	sandy loam 1.5% O.M.	nominal	Dixon, 1988

Species	Effect (a) (% decrease)	Endpoint	Concentration ($mg \cdot kg^{-1}$)	Form of Cd (exposure period)	Soil pH	Test Substrate	Extraction Method	Reference
Lettuce *L.sativa*	seedling emergence	NOEC	44	$CdCl_2$ (120 hours)	4-4.2	artificial soil (Green et al.,1989)	HNO_3/ H_2O_2/HCl digest.	Environment Canada, 1995
		EC_{25}	94					
	seedling emergence (29%)	LOEC	102					
	seedling emergence	EC_{50}	143					
Radish *R. sativa*	seedling emergence	NOEC	99	$CdCl_2$ (72 hours)	4-4.2			
		EC_{25}	157					
	seedling emergence (40%)	LOEC	174					
		EC_{50}	205					
	seedling emergence							
Earthworm *E.fetida*	survival	NOEC	430	$CdCl_2$ (14 days)	4.0-4.3			
	survival (54%)	LOEC	1033					
	survival	LC_{25}	700					
		LC_{50}	1100					
Turnips *B. rapa*	growth	EC_{50}	111.5	$CdCl_2$ (10 days)	6.1	sandy loam 1.3% O.C. 9.9% clay	nominal	Gunther & Pasterner, 1990
Beech *Fagus sylvatica*	shoot elongation (61%)	EC	20.2	$CdNO_3$ (21 months)	4.8-3.7 (b)	mix of sand, peat and forest soil	NH_4Ac extraction	Hagemeyer et al., 1993
Soybean *G. max*	yield (14%)	EC	2.5	$CdCl_2$ (5 weeks)	6.7	silt clay loam 4% O.M.	$HClO_4$ + HNO_3 digestion	Haghiri, 1973
Wheat *T. aestivum*	yield (21%)	EC	2.5					
Maize *Z. mays*	root elongation (43%)	EC	25	$CdCl_2$ (5 days)	6.5	loamy sand 4% O.M.	nominal	Hassett et al., 1976
				$CdCl_2$ (95 days)	5.1	silt loam 11.8% O.M.	nominal	John, 1973
Peas *Pisum sativum*	vine yield (87%)	EC	200					
	seed yield (99%)	EC	200					
	pod yield (92%)	EC	200					
	root yield (72%)	EC	200					
Radish *R. sativus*	top yield (24%)	EC	40	(45 days)				
	top yield (92%)	EC	200					
	tuber yield (93%)	EC	200					
Cauliflower *Brassica oleracea*	leaf yield (97%)	EC	200	(70 days)				
	root yield (90%)	EC	200					

Species	Effect (a) (% decrease)	Endpoint	Concentration (mg·kg⁻¹)	Form of Cd (exposure period)	Soil pH	Test Substrate	Extraction Method	Reference
Carrot *D.carota*	tuber yield (96%) root yield (86%)	EC EC	200 200	(130 days)				
Lettuce *L. sativa*	leaf yield (91%)	EC	200	(35 days)				
Broccoli *Brassica oleracea*	leaf yield (63%)	EC	200	(60 days)				
Spinach *S. oleracea*	leaf yield (96%) root yield (96%)	EC EC	40 40	(55 days)				
Oats *A. sativa*	grain yield (36%)	EC	40	$CdCl_2$ (100 days)				
Yellow poplar *Liriodendron tulipifera*	root dry weight (77%)	EC	133.5	$CdCl_2$ (17 weeks)	4.8	sand 1.92% O.M.	HNO3 digestion	Kelly et al., 1979
White pine *Pinus strobus*	root dry weight (49%)	EC	133.5					
Choke cherry *Prunus virginiana*	root dry weight (87%)	EC	133.5					
Lobolly pine *Pinus taeda*	root dry weight (43%)	EC	133.5					
Yellow birch *Betuda alleghniensis*	root dry weight (73%)	EC	133.5					
Radish *R. sativa*	root growth shoot growth	EC_{50} EC_{50}	170 190	CdO (42 days)	5.4	loamy sand	HCl + HNO3 digestion	Khan & Frankland, 1983
	shoot growth root growth	EC_{50} EC_{50}	70 44	$CdCl_2$ (42 days)				

Species	Effect (a) (% decrease)	Endpoint	Concentration ($mg\cdot kg^{-1}$)	Form of Cd (exposure period)	Soil pH	Test Substrate	Extraction Method	Reference
Oat, *A. sativa*	root biomass (25%)	EC	10	$CdCl_2$ (42 days)	5.4	brown earth	nominal	Khan & Frankland, 1984
Radish, *R. sativum*	root biomass (32%)	EC	50					
Wheat, *T. aestivum*	root biomass (61%)	EC	50					
Earthworm, *Lumbricus rubellus*	mortality	NOEC LC_{100}	150 1000	$CdCl_2$ (6 weeks)	7.3	sandy loam, 8% O.M., 17% clay	HCl digestion	Ma 1982
Corn, *Zea mays*	yield	EC_{21} (c)	5.4	$CdNO_3$ (2 months)	5.3	acid sandy clay 1.5% O.M.	aqua regia extraction	Mench et al., 1989
Wild bergamot *Monarda fistulosa*	shoot growth (23%)	EC	10	$CdCl_2$ (6 weeks)	4.8	sandy mesic typic Upsisamment 1.93% O.M.	HNO3 extraction	Miles & Parker, 1979a
Bluegrass, *Poa pratensis*	shoot growth (90%)	EC	30					
Blazing-star *Liatris spicata*	shoot growth (80%)	EC	30					
Timbleweed *Anemone cylindrica*	shoot growth (80%)	EC	30					
Little bluestem *Andropogon scoparius*	shoot growth (21%)	EC	10					
Poison-ivy, *Rhus radicans*	shoot growth (63%)	EC	30					
Black-eyed Susan *Rudbeckia hirta*	shoot growth (79%)	EC	10					
Little bluestem *A. scoparius*	shoot growth total weight root growth	EC_{25} EC_{25} EC_{25}	27.57 21.75 18.62	$CdCl_2$ (12 weeks)	4.8	sandy mesic typic Upsisamment 1.93% O.M.	nominal	Miles & Parker, 1979b

Species	Effect (a) (% decrease)	Endpoint	Concentration (mg·kg^{-1})	Form of Cd (exposure period)	Soil pH	Test Substrate	Extraction Method	Reference
Soybean *G. max*	shoot yield (23%) shoot yield (26%) shoot yield (33%) shoot yield (34%) shoot yield (47%) shoot yield (69%) shoot yield (51%) shoot yield (52%)	EC EC EC EC EC EC EC EC	10 100 10 100 100 100 100 10	$CdCl_2$ (4 weeks)	5.7 5.5 6.1 6.1 6.5 6.0 7.0 4.5	loamy sand silt loam silt loam silt clay loam silt loam silt loam silt loam silt loam	nominal	Miller et al., 1976
Corn, *Z. mays*	shoot growth (28%)	EC	2.5	$CdCl_2$ (31 days)	6.0	loamy sand	nominal	Miller et al., 1977
Rice, *O. sativa*	plant growth (31%) plant growth (8%)	EC EC	1000 30	CdO (15 weeks)	5.95	alluvial soil	nominal	Muramoto et al., 1990
Wheat, *T estiva*	plant growth (97%) plant growth (85%) plant growth (30%)	EC EC EC	1000 100 30	(23 weeks)				
Earthworm, *E. fetida*	survival	LC_{50}	1843	$Cd(NO_3)_2$ (2 weeks)	6.0	artificial soil, (EEC, 1982)	(d)	Neuhauser et al., 1985
Wheat *T. aestivum*	plant growth (NQ)	LOEC	1.8	CdAc (4 weeks)	5.6	acidic cambisol, (38.7% sand, 1.87 % O.M.)	nominal	Reber, 1989
		LOEC	7		6.9	phaeosem, (3.85% sand; 2.1% O.M.)		
		LOEC	14		7.0	sandy hortisol, (88% sand; 2.62% O.M.)		
Cotton Gossypium hirsutum cv. Acala SJ2	leaf yield (60%) leaf yield (84%) stem yield (78%)	EC EC EC	300 600 300	$CdSO_4$ (5 weeks)	6.8	Yolo silt loam	nominal	Rehab & Wallace, 1978
Cotton G. spp. cv Giza 45	leaf yield (75%) stem yield (83%) leaf yield (86%)	EC EC EC	300 300 600					

Species	Effect (a) (% decrease)	Endpoint	Concentration ($mg \cdot kg^{-1}$)	Form of Cd (exposure period)	Soil pH	Test Substrate	Extraction Method	Reference
Wheat T. aestivum	dry matter production (79%) grain yield (58%) yield (NQ) dry matter production (15%)	EC EC LOEC EC	100 100 4.8 12.5	$CdSO_4$ (45 days) (from seed) (45 days) (45 days)	8.1	loamy sand 0.18% O. C.	nominal	Singh et al., 1989
Earthworm E. fetida	cocoon production	NOEC EC_{50}	39.2 46.3	$CdNO_3$ (56 days)	6.3	artificial soil (OECD, 1984)	HNO3 digestion	Spurgeon et al., 1994
Earthworm E. andrei	growth survival sexual development growth sexual development	EC_{50} LC_{50} NOEC NOEC EC_{50}	33 253 <10 18 27	$CdCl_2$ (12 weeks)	6.7-6.8	artificial soil 20% clay 10% peat 69% sand	nominal	van Gestel et al., 1991
Earthworm E. andrei	growth cocoon production % fertile cocoons	NOEC NOEC NOEC	100 <10 100	$CdCl_2$ (3 weeks)	6.0	artificial soil , 20% clay,10% peat, 69% sand	nominal	van Gestel et al., 1992

a: The EC endpoints represent the effects concentration as calculated by the CCME from the data presented by the authors.
b: pH conditions in the soil changed from 4.8 to 3.7 during the 2 years experimental period.
c: The concentration reported here comes from a single concentration study.
d: The extraction method is reported in another paper that was published in german and therefore was not identified.
(NQ): Proportion of individuals affected in the population and amount of effect are not quantifiable.

Table 10. Selected microbial toxicological studies for cadmium

Species/Process	Effect (a) (% decrease)	Endpoint	Concentration (mg·kg^{-1})	Form of Cd (exposure period)	Soil pH	Test Substrate	Extraction Method	Reference
N-mineralization	inhibition (39%) inhibition (27%) inhibition (17%) inhibition (18%)	EC (b) EC (b) EC (b) EC (b)	5 5 5 5	$CdSO_4$ (20 days)	7.8 6.6 5.8 7.4	7.8% O.C., 30% clay 2.95% O.C., 45% clay 2.58% O.C., 23% clay 5.45% O.C., 34% clay	nominal	Liang & Tabatabai, 1977
N-mineralization	inhibition (55%) inhibition (88%)	EC EC	45 209	$CdSO_4$ (9 years)	6.0	sandy cambisol 1.2% O.C., 9% clay	aqua regia	Wilke, 1989
Denitrification	accumulation of nitrites	EC35	250	(21 days)	6.75	silt loam 1.8% O.C., 28.1% clay	nominal	Bollag & Barabasz, 1979
Nitrification	reduction	EC60	1000	$CdSO_4$ (35 days)	4.8	5.8% O.M., 9.4% clay	nominal	Bewley & Stotzky, 1983c
CO_2 evolution	reduction (NQ) reduction (NQ) reduction (NQ)	EC EC EC	2.6 2.7 7.8	Cd acetate	7.0 6.9 5.6	2.62% O.M., 3.16% loam 2.19% O.M., 21,25% loam 1.67% O.M., 7.02 loam	nominal	Reber, 1989
CO_2 evolution	reduction reduction	EC17 EC11	10 100	$CdSO_4$ (8 weeks)	4.9	loamy sand 2.1% O.C., 5.2% clay	nominal	Cornfield, 1977
CO_2 evolution	inhibition (35%) inhibition (35%) inhibition (35%) inhibition (35%) inhibition (30%)	EC EC EC EC EC	562 562 562 562 562	$CdSO_4$ (45 days)	6.7 6.2 7.2 7.0 8.2	3.1% O.M., 27% clay 64% O.M. 1.7% O.M., 21% clay 5.5% O.M., 51% clay 4.7% O.M., 11% clay	nominal	Lighthart et al., 1983
CO_2 evolution	reduction (20%) reduction (43%) reduction (47%) reduction (19%) reduction (34%)	EC EC EC EC EC	400 1000 1000 1000 8000	$CdCl_2$ (43 weeks) (70 weeks) (90 weeks) (82 weeks) (80 weeks)	6.0 7.0 7.7 4.4 7.5	sandy loam, 5.7% O.M. sand, 1.6%O.M. silty loam, 2.4% O.M. sandy peat, 12.8% O.M. clay, 3.2% O.M.	nominal	Doelman & Haanstra, 1984

a: The EC endpoints represent the effects concentration as calculated by the CCME from the data presented by the author(s)
b: The concentration reported here comes from a single concentration study.
(NQ): Proportion of individuals affected in the population and amount of effect are not quantifiable

Table 11. Selected livestock and wildlife toxicological studies for cadmium

Species	Effect (% decrease)	Endpoint (a)	Diet concentration (mg/kg)	Average dose (mg/kg/day)	Form of Cd (exposure period)	Reference
Calves	body weight gain (22%)	EC	15 mg/kg body weight (b)	6.43	$CdCl_2$ (12 weeks)	Lynch et al., 1976
	survival time (25%)	EC	15 mg/kg body weight (b)	6.43		
Lambs	body weight gain (21%)	EC	60	4.56	$CdCl_2$ (191 days)	Doyle et al., 1974
Quail	body weight (30%)	EC	75	41.7	$CdCl_2$ (2 weeks)	Spivey Fox et al., 1971
Quail	body weight (15%)	EC	75	15.46	$CdCl_2$ (6 weeks)	Richardson et al., 1974
Chicks	body weight gain (36%)	EC	75	15	$CdCl_2$ (3 weeks)	Freeland & Cousins, 1973
Pigs	average daily weight gain (87%)	EC	95	9.98	$CdCl_2$	Pond et al., 1966
Calves	weight gain (30%)	EC	160	4.78	$CdCl_2$ (12 weeks)	Powell et al., 1964
	body weight (65%)	EC	640	19.15		
Swine	body weight gain (69%)	EC	450	46.7	$CdCl_2$ (6 weeks)	Cousins et al., 1973
	body weight gain (96%)	EC	1350	140		

a: The EC endpoints represent the effects concentration as calculated by the CCME from the data presented by the author(s).
b: This particular cadmium diet was given three times a week to the animals.

Table 12. Soil Quality Guidelines for Cadmium.

Guidelines		LAND USE		
		Agriculture (mg/kg)	Residential/Parkland (mg/kg)	Commercial/Industrial (mg/kg)
TEC (a) or ECL	(20th percentile)	10	10	Not applicable
	(25th percentile)	10	10	27
	(30th percentile)	14	14	30
	(35th percentile)	Not applicable	Not applicable	31.6
Nutrient and energy cycling check		18	18	92
SQC_{SC}		10	10	27
SQC_I		3.8	Not applicable	Not applicable
SQC_E		3.8	10	27
Ontario Background Levels (OMEE 1994)		1.0	1.0	No value
Interim Remediation Criteria (CCME 1991)		3	5	20

(a): As per the CCME 1996 protocol theTEC for Agriculture and Residential/Parkland corresponds to the 25th percentile of the effects and no effects data distribution using the Weight of Evidence method, while the ECL for Commercial/Industrial corresponds to the 25th percentile of the effects data distribution. The other percentiles are presented for comparison purpose only.

CANADIAN SOIL QUALITY
GUIDELINES FOR CADMIUM:
ENVIRONMENTAL