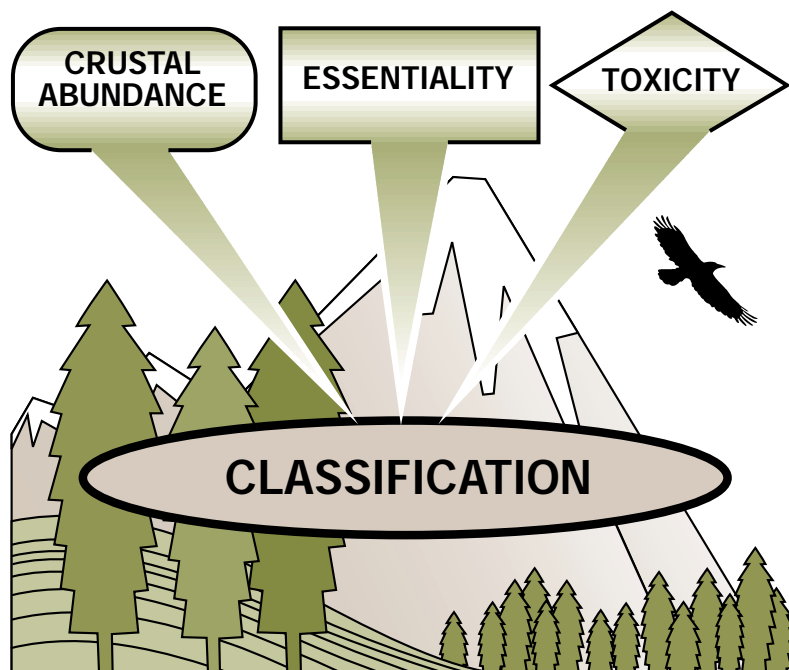

HAZARD CLASSIFICATION OF METALS IN TERRESTRIAL SYSTEMS

A Discussion Paper

by
Anne Fairbrother, D.V.M., Ph.D.
and
Lawrence A. Kapustka, Ph.D.



A Publication by the International Council
on Metals and the Environment

This book has been published by the International Council on Metals and the Environment (ICME) as part of a series of publications discussing issues relevant to environmental and/or health-related policies affecting the mining and metals sector. It is believed that the topics examined are of concern, not only to the non-ferrous and precious metals mining and producing sectors, but also to others, including policy makers, regulators, educators and the public at large. ICME hopes that these publications provide insight into what are often difficult and complex issues. While the views expressed in these publications are those of the authors, ICME welcomes questions and comments on their perspectives and the information they provide. The Council also appreciates suggestions regarding other issues of public importance for future publications.

Founded in 1991, ICME is a non-governmental organization that promotes the development and implementation of sound environmental and health policies and practices in the production, use, recycling and disposal of non-ferrous and precious metals. For further information about ICME, or to obtain additional copies of this publication or other ICME publications, please contact:

The International Council on Metals and the Environment

294 Albert Street, Suite 506

Ottawa, Ontario

CANADA K1P 6E6

Tel: (613) 235-4263

Fax: (613) 235-2865

e-mail: info@icme.com

<http://www.icme.com>

“Hazard Classification of Metals in Terrestrial Systems - A Discussion Paper” by Anne Fairbrother and Lawrence A. Kapustka.

First Printing, May 1997.

ISBN 1-895720-21-4

HAZARD CLASSIFICATION OF METALS IN TERRESTRIAL SYSTEMS

A Discussion Paper

by
Anne Fairbrother, D.V.M., Ph.D.
and
Lawrence A. Kapustka, Ph.D.



**A Publication by the International
Council on Metals and the Environment**

TABLE OF CONTENTS

Foreword	iii
Executive Summary	v
CHAPTER 1. Introduction	1
CHAPTER 2. Classification System Outline	3
2.1 Environmental Fate	5
2.1.1 Elemental Abundance, Essentiality and Toxicity	5
2.1.2 Persistence and Transformation	9
2.1.3 Bioaccumulation	11
2.2 Environmental Effects	12
2.2.1 Intrinsic Toxicity	12
2.2.2 Test Species	13
2.2.2.1 Standard test species	15
2.2.3 Data Quality Criteria	16
CHAPTER 3. Combination of Properties to Form Criteria	17
CHAPTER 4. Selection of Cut-Off Values	19
4.1 Crustal Abundance	19
4.2 Toxicity	20
4.2.1 Toxicity to Soil Organisms	24
4.2.2 Slope Factor	25
4.3 Final Hazard Classification	25
CHAPTER 5. Conclusion	27
CHAPTER 6. References	29

TABLES AND FIGURES

Tables	Page
1. Naturally Occurring Elements: Their Abundance and Essentiality	6-7
2. Categories of Origin of Mineral Nutrient Requirements	8
3. Recommended Species for Hazard Identification and Classification of Chemicals in the Soil Environment Using Standard Protocols	15
4. Generalized Elemental Requirements (mg/kg soil) of Plants	22
5. Trace Element Effects Concentrations (mg/kg soil) for Plants	22

Figures	
1. Relationship Between Nordic and Natural Element Hazard Classification Schemes	4
2. Log Crustal Concentration of the 70 Most Abundant Elements, Required Concentrations (ppm) for Plants, and Phytotoxic Levels Arranged in Descending Order of Crustal Abundance	10
3. Threshold Concentration	13
4. Slope of Dose–Response Relationships	14
5. Three-Stage Hazard Classification Process	17
6. Intrinsic Hazard Classification Based on Toxicity and Slope of Dose–Response Relationship	18
7. Initial Hazard Classification Flow Chart	20
8. Typical Dose–Response Curve for: (a) Essential Elements; and, (b) Non-Essential Elements	21
9. Toxicity Classification Scheme Flow Chart	23
10. Final Hazard Classification Scheme Flow Chart	24

Foreword

At the present time, there exist very few validated tests for evaluating the terrestrial toxicity of metals and metal compounds. Indeed, a classification system for metals and metal compounds in the terrestrial environment has yet to be developed. Existing test methods and proposed criteria, most of which were developed for organic substances, need to be modified, taking into account, among others, the essentiality (deficiency vs toxicity) of some metals and their transformation to bioavailable forms.

This document offers, for discussion purposes, a novel approach to the evaluation and classification of terrestrial hazards related to metals and metal compounds. In general, the document recommends a hazard classification system that uses crustal abundance of an element as an initial screening step prior to the consideration of toxicity. Special care is also taken with essential elements to ensure that nutritional deficiency responses are distinguished from toxicity responses.

ICME hopes that this document will contribute to discussions related to the development of an appropriate system for hazard evaluation and classification of metals and metal compounds.

Gary Nash
Secretary General
ICME

Executive Summary

To help meet the Organisation for Economic Cooperation and Development (OECD) goal of harmonizing criteria for hazard classification, the Nordic Project Group recently published a draft scheme for classifying chemicals in the terrestrial environment. Although this proposed scheme is satisfactory in many ways, it focuses mainly on synthetic organic chemicals and so fails to adequately address the environmental attributes of natural inorganic substances. Because metals, metal compounds and metalloids belong to this latter group of substances, their hazard classification needs to reflect their unique role in terrestrial environments.

In particular, metals, minerals and their derivative compounds require separate consideration due to two major attributes not shared with synthetic organic substances. First, as elements, these substances by nature persist indefinitely, so that measures of persistence become meaningless when differentiating among them. Second, many elements are required macro- and micro-nutrients, requiring classification schemes that account for critical nutritional concentrations and required bioaccumulation processes.

The authors propose that the Nordic Project Group scheme be augmented by a hazard classification for metals, minerals and their derivatives that reflects their properties in the soil compartment of the environment. A hazard classification scheme is presented which is compatible with the strengths of the Nordic Project Group's proposal. The major goal is to create a hazard classification scheme for inorganic substances that is simple and unambiguous.

The classification system is based first on the crustal abundance of the element in question. Established literature supports the position that relative crustal abundance gives a conservative initial estimate of environmental hazard. The initial hazard class is then modified by toxicity studies based on lowest EC_{50} and the slope of the dose-response curve derived from a suite of standard toxicity tests. The authors recommend test species for establishing EC_{50} toxicity responses in the soil compartment. In general, the final hazard class depends on crustal abundance modified by toxicity, with toxicity first being modified by the dose-response relationship. Special care is taken with essential trace elements to make sure nutritional deficiency responses to elements of concern are not confused with toxicity responses.

This hazard classification scheme recognizes the significant environmental properties of natural elements such as metals and metalloids, and should provide a necessary and appropriate addition to the Nordic Project Group proposal.

CHAPTER 1

Introduction

For several years, the Organisation for Economic Cooperation and Development (OECD) has been working to harmonize criteria developed independently by member countries for hazard classification of chemicals in the aquatic environment. Recently, attention has been given to developing similar classification schemes for terrestrial systems. In April 1996, the Nordic Project Group of the Terrestrial Effects Working Group within the OECD Hazard Assessment Advisory Body published a draft of its proposed terrestrial classification scheme, *Environmental Hazard Classification Criteria for Chemical Substances: Terrestrial Environment – Fate in the Soil and Soil Compartment Effects*. This document provided a reasonable proposed classification scheme and background discussion on the behaviour of chemicals in the soil compartment. However, as evidenced by the examples given, the discussions of environmental chemistry and fate, and the classification parameters chosen, the proposed classification scheme was developed for synthetic organic compounds and was modelled mainly on the aquatic hazard classification scheme. It did not adequately address naturally occurring metals, minerals and their derivative compounds.

Environmental properties of naturally occurring elements differ from those of synthetic organic compounds in two important ways. First, naturally occurring elements such as metals, metalloids and minerals are fundamental constituents of the environment, whereas synthetic organic contaminants are generally novel compounds for which organisms may have had limited time to evolve tolerance or avoidance behaviours. Therefore, naturally occurring metals and minerals and their derivative forms are, by definition, persistent environmental constituents while synthetic organic compounds differ significantly in their environmental half-lives. Second, some naturally occurring elements such as nitrogen, phosphorus and calcium are required macro-nutrients for plants and animals, while others, such as copper and zinc, are required micro-nutrients. Synthetic organic compounds are never required nutrients. Thus, a hazard classification scheme for the unintentional introduction of anthropogenically concentrated amounts of naturally occurring metals and minerals must differ to some extent from that developed for synthetic organic chemicals.

We offer here a modification of the classification scheme proposed by the Nordic Working Group for the terrestrial environment that could be used for classifying envi-

ronmental hazards of naturally occurring metals, metal compounds and their derivatives.¹ It is not meant to replace the proposed classification scheme, but to supplement its use. It retains many of the same philosophies, cut-off values and approaches described by the current draft scheme, and makes only those modifications necessary to account for the natural occurrence and resulting nutrient requirements of metals and their derivative compounds.

¹ Although the focus of this paper is the development of a proposed hazard classification scheme for metals, minerals and their derivatives, the concepts presented could be applied to all other naturally occurring elements.

CHAPTER 2

Classification System Outline

As with the Nordic Group classification, this classification system for metals and metal compounds is for the soil compartment and is not meant to construe hazard to the above-ground system beyond effects to terrestrial plant communities. Also, as with any hazard-ranking system, it must be simple and unambiguous. Only limited technical and scientific knowledge should be needed to classify a substance; different persons, regardless of their expertise, should be able to get the same answer from the same starting information.

Hazard is the innate capacity of a material to cause harm to an organism with which it comes into contact. It has been variously defined as the “intrinsic toxicity” of a compound (NAS, 1983) or “the likelihood that injury will occur in a given situation or setting” (Plaa, 1989). This second definition lends confusion to contemporary discussions, as it is indistinguishable from general definitions of “risk.” Therefore, to develop a hazard classification system, we will define “intrinsic toxicity” as the ability of a compound to cause a toxic response in an organism under standardized conditions of exposure and bioavailability. Hazard classification of synthetic compounds defines the intrinsic toxicity of a compound, but also considers environmental persistence and bioaccumulation potential. This general framework is equally applicable to synthetic organic compounds or inorganic substances in aquatic or terrestrial systems, although the methods used to quantify toxicity, persistence and bioaccumulation differ. Persistence of naturally occurring elements is infinite. Biogeochemical cycling processes alter the relative distribution of various chemical moieties, but again, these derivative forms persist indefinitely. One could consider equilibrium positions and rate constants in hazard ranking; however, they require a high level of sophisticated testing and models with parameters that vary according to site-specific conditions. As such, equilibrium and rates of change are best dealt with on a case-by-case basis, instead of as part of the general hazard-ranking process. Consideration of persistence is therefore not a useful construct in ranking the hazard of naturally occurring substances.

In elaborating the criteria for hazard classification, a minimum set of information is required. The following steps reflect the minimum required information:

- a. selection of relevant parameters/intrinsic properties for the criteria;
- b. combination of the properties to form the criteria;
- c. selection of cut-off values;

-
- d. identification of appropriate test methods and toxicity endpoints; and,
 - e. minimal data quality requirements for toxicity tests.

While these steps in hazard classification are the same for both organic and inorganic substances, the component parts of each step differ significantly. Therefore, the first decision made when classifying a substance for potential environmental hazard is to determine whether it is a synthetic organic substance or a naturally occurring element. If it is a synthetic organic substance, the classification system proposed by the Nordic Working Group should be followed. If it is a naturally occurring element, the classification system proposed here should be used (Figure 1). Special consideration may be required to deal with essential elements (Table 1).

The hazard classification proposed for metals and metal compounds diverges further from that of synthetic organic compounds. First, it classifies the compound based on its environmental properties (e.g., crustal abundance). Then, it modifies the classification according to intrinsic toxicity values consideration of the entire dose–response relationship, not just a measure of the soil concentration where toxicity effects begin to occur.²

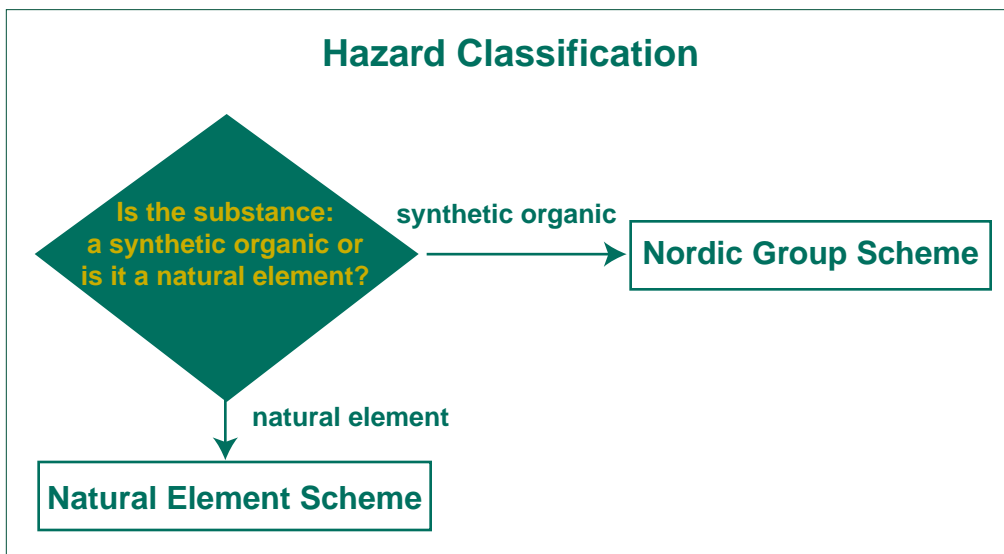


FIGURE 1.
Relationship Between Nordic and Natural Element Hazard Classification Schemes

² Minerals and other derivative compounds that contain more than one metal or naturally occurring element would be classified initially based on the metal with the highest hazard classification rank.

2.1 Environmental Fate

In addition to being essential nutrients, naturally occurring elements, such as metals, metalloids and minerals, differ most significantly from synthetic organic compounds in terms of persistence and bioaccumulation. In general, synthetic organic compounds that have a high potential for persistence and bioaccumulation are more hazardous than compounds in the same toxicity range that do not have those environmental properties. For naturally occurring elements, however, comparisons based on persistence are virtually meaningless because these elements are all intrinsically part of the Earth's crust and are therefore indefinitely persistent. Because of this, plants and animals have evolved homeostatic mechanisms to use these elements (e.g., the required micro-nutrients) and actively or passively exclude them to maintain tissue concentrations within a desirable range. Some plant species have evolved mechanisms to tolerate high exposure to some metal compounds with no apparent adverse consequences and even to concentrate metals in their tissues as a defence against herbivory (selenium accumulation in plants is an example of this adaptation). In general, the more naturally abundant an element is, the less of a hazard it and its derivative substances pose to soil organisms; however, homeostatic mechanisms can be overwhelmed for any substance at a sufficiently high exposure concentration. Furthermore, a given amount of an anthropogenically added material would have less of an effect if the substance naturally exists in the environment in high amounts than if it existed in very low amounts. That is, the proportional amount added would be very small for elements naturally high in concentration. Therefore, hazard classification of metals, minerals and their derivative compounds can be based initially on relative crustal abundance. This is analogous to the classification of synthetic organic compounds based on the soil sorption coefficient (K_d) or constant (K_{oc}), or the octanol/water partition coefficient ($\log K_{ow}$).

2.1.1 Elemental Abundance, Essentiality and Toxicity

The theme developed in this section relates to the general relationship between essentiality, toxicity and crustal abundance. The thesis was first developed by McClendon (1976). Additional background information comes from Skujins (1987), Kabata-Pendias and Pendias (1992) and Bidwell (1979). These sources rely on nearly 60 years of experimentation in agronomy and plant physiology conducted to determine the optimal soil conditions for maximizing plant growth and reproduction. This long-term effort provides a sound scientific basis for using relative crustal abundance in the initial classification of natural elements for their potential hazard to soils.

Over time, organisms have evolved from depending primarily on inorganic materials to a protein-based organic system. However, inorganic compounds are still required by most enzyme systems. It is intuitively logical that organisms evolved to use in their

TABLE 1.
Naturally Occurring Elements: Their Abundance and Essentiality

Element	Symbol	Essentiality*	Atomic Number	Atomic Weight	Crustal Conc. (molar)**	Abundance Rank
Actinium	Ac	N	89	227.03		91
Aluminum	Al	N	13	26.98	3.91E+00	3
Antimony	Sb	N	51	121.75	1.60E-06	57
Argon	Ar	N	18	39.95		73
Arsenic	As	a	33	74.92	2.40E-05	45
Astatine	At	N	85	210.00	1.56E-04	38
Barium	Ba	N	56	137.33	3.30E-03	18
Beryllium	Be	N	4	9.01	3.10E-04	33
Bismuth	Bi	N	83	208.98	1.00E-09	69
Boron	B	P	5	10.81	9.30E-04	27
Bromine	Br	N	35	79.90	3.10E-05	43
Cadmium	Cd	N	48	112.41	1.80E-06	56
Calcium	Ca	P, A	20	40.08	9.05E-01	6
Carbon	C	P, A	6	12.01	1.70E-02	13
Cerium	Ce	N	58	140.12	4.00E-04	31
Cesium	Cs	N	55	132.91	2.20E-05	46
Chlorine	Cl	P, A	17	35.45	3.70E-03	17
Chromium	Cr	N	24	52.00	2.00E-03	21
Cobalt	Co	p, A	27	58.93	4.30E-04	30
Copper	Cu	P, A	29	63.55	8.70E-04	28
Dysprosium	Dy	N	66	162.50		82
Erbium	Er	N	68	167.26		84
Europium	Eu	N	63	151.96		79
Fluorine	F	P, A	9	19.00	3.30E-02	12
Francium	Fr	N	87	223.00		90
Gadolinium	Gd	N	64	157.25		80
Gallium	Ga	N	31	69.72	2.15E-04	34
Germanium	Ge	N	32	72.59	2.10E-05	47
Gold	Au	N	79	196.97	2.00E-08	66
Hafnium	Hf	N	72	178.49	1.70E-05	49
Helium	He	N	2	4.00		71
Holmium	Ho	N	67	164.93		83
Hydrogen	H	P, A	1	1.01	1.40E+00	4
Indium	In	N	49	114.82	1.00E-06	58
Iodine	I	A	53	126.90	4.00E-06	55
Iridium	Ir	N	77	192.22	5.00E-09	68
Iron	Fe	P, A	26	55.85	9.00E-01	7
Krypton	Kr	N	36	83.80		74
Lanthanum	La	N	57	138.91	2.00E-04	36
Lead	Pb	N	82	207.20	6.30E-05	41
Lithium	Li	N	3	6.94	2.90E-03	19
Lutetium	Lu	N	71	174.97		87
Magnesium	Mg	P, A	12	24.31	8.60E-01	8
Manganese	Mn	P, A	25	54.94	1.70E-02	14
Mercury	Hg	N	80	200.59	4.00E-07	61
Molybdenum	Mo	P, A	42	95.94	1.50E-05	50
Neodymium	Nd	N	60	144.24	2.00E-04	37
Neon	Ne	N	10	20.18		72
Nickel	Ni	P, A	28	58.69	1.30E-03	24
Niobium	Nb	N	41	92.91	2.15E-04	35
Nitrogen	N	P, A	7	14.01	1.40E-03	23
Osmium	Os	N	76	190.20	2.60E-08	65

TABLE 1. (cont.)

Element	Symbol	Essentiality*	Atomic Number	Atomic Weight	Crustal Conc. (molar)**	Abundance Rank
Oxygen	O	P, A	8	16.00	2.90E+01	1
Palladium	Pd	N	46	106.42	9.40E-08	62
Phosphorus	P	P, A	15	30.97	3.40E-02	11
Platinum	Pt	N	78	195.08	5.00E-08	64
Polonium	Po	N	84	254.00		88
Potassium	K	P, A	19	39.10	6.62E-01	9
Praseodymium	Pr	N	59	140.91	6.00E-05	42
Promethium	Pm	N	61	145.00		77
Protactinium	Pa	N	91	231.04		92
Radium	Ra	N	88	226.03	1.00E-13	70
Radon	Rn	N	86	71.00		89
Rhenium	Re	N	75	186.21	5.00E-09	67
Rhodium	Rh	N	45	102.91	5.00E-08	63
Rubidium	Rb	N	37	85.47	1.00E-03	26
Ruthenium	Ru	N	44	101.07	1.00E-04	39
Samarium	Sm	N	62	150.36		78
Scandium	Sc	N	21	44.96	4.90E-04	29
Selenium	Se	A	34	78.96	6.00E-07	60
Silicon	Si	p	14	28.09	9.86E+00	2
Silver	Ag	N	47	107.87	6.50E-07	59
Sodium	Na	p, A	11	22.99	1.23E+00	5
Strontium	Sr	N	38	87.62	4.30E-03	16
Sulphur	S	P, A	16	32.06	8.00E-03	15
Tantalum	Ta	N	73	180.95	1.10E-05	51
Technetium	Tc	N	43	98.00		75
Tellurium	Te	N	52	127.60	7.80E-05	40
Terbium	Tb	N	65	158.93		81
Thallium	Tl	N	81	204.38	1.00E-05	52
Thorium	Th	N	90	232.04	3.10E-05	44
Thulium	Tm	N	69	168.93		85
Tin	Sn	N	50	118.69	1.70E-05	48
Titanium	Ti	N	22	47.88	9.20E-02	10
Tungsten	W	N	74	183.85	8.00E-06	53
Uranium	U	N	92	238.03	8.00E-06	54
Vanadium	V	N	23	50.94	2.70E-03	20
Xenon	Xe	N	54	131.29		76
Ytterbium	Yb	N	70	173.04		86
Yttrium	Y	N	39	88.91	3.70E-04	32
Zinc	Zn	P, A	30	65.38	1.10E-03	25
Zirconium	Zr	N	40	91.22	1.80E-03	22

* Compiled from Alloway (1995), NRC (1980), Bidwell (1979) and McClendon (1976). Here, essentiality means that the element is required as a structural component of a cell constituent or as a co-factor for an enzyme. Elements that may substitute for essential elements (e.g., As substituting for P in plants) are not considered essential. Also, elements that stimulate growth, as Cd sometimes does, but do not meet the definition of essentiality above were considered non-essential.

N= not required; P = required by all plants; p = required by some plants; A = required by all animals; a = required by some animals.

** Crustal abundance concentrations were adapted from McClendon (1976).

enzyme systems those metals that are relatively abundant. During the course of evolution, some of the less abundant compounds were able to substitute for the more abundant ones and have become required nutrients or can substitute for required ones. There are 17 elements commonly required by some plants (H, O, C, N, K, Ca, Mg, P, S, Cl, B, Fe, Mn, Zn, Cu, Mo and Ni) and three less commonly required elements (Co, Na, Si). Nineteen of these 20 elements are among the 30 most abundant elements on Earth (Table 1). Molybdenum, the least abundant of this group, ranks 50th in crustal abundance. Animals have additional required elements, including I and Se which rank 55th and 60th, respectively. Physical-chemical properties, such as solubility, electromagnetism, ionic size and double-bonding potential, account for deviations from a one-to-one correspondence of crustal abundance and nutritional requirement. McClendon (1976) argued for the evolutionary nature of the essentiality of naturally occurring substances and developed four observational hypotheses concerning the origin of the nutritional requirements of plants and animals for the essential elements (Table 2).

TABLE 2.
Categories of Origin of Mineral Nutrient Requirements

Code	Hypothesis	Elements
H-I	a unique requirement dating from the origin of life	H, K (vs. Na); Mg (vs. Ca); C, N, O, P, S and Fe
H-II	a unique requirement acquired later	B, Se and I
H-III	a primordial requirement which was satisfied by a number of elements, evolutionary adaptation being made to the most abundant member	K vs. Rb; Mg vs. Be(?); S vs. Se; Cl vs. Br; H vs. F(?); and Zn and Mn vs. various metals
H-IV	an acquired requirement which was satisfied by a number of elements, evolutionary adaptation being made to the most abundant member	Ca vs. Sr; Na vs. Li(?); Mo vs. V; and Si vs. Ge

Source: McClendon (1976)

Of the essential elements, only those that are assimilated as gases (O, H, C and N) are required by plants at concentrations greater than occur in the Earth's crust. A plot of the logarithm of crustal concentration in order of decreasing crustal abundance illustrates that other plant nutrient requirements are between 1 to 2 orders of magnitude lower than crustal concentrations (Figure 2). This may well reflect evolutionary adjustments to the typical bioavailable concentration of each element. Organisms having requirements for concentrations greater than those typically found in the environment would have highly restricted distribution potential. Dynamic shifts in climate and geomorphic conditions (e.g., mountain formation, changes in sea level) place strong negative selection pressures on species with highly specialized local requirements. Thus, evolutionary events would eliminate individuals and/or species that had an elemental requirement that was higher than that typically available.

Phytotoxic levels, with the apparent exception of vanadium (V), are at or above crustal concentration levels (Figure 2). This is also intuitively appropriate: if toxicity were to occur routinely at concentrations less than crustal abundance, large portions of the landscape would be barren. For the 14 elements whose phytotoxic levels have been listed here, average phytotoxic thresholds occur within 2 orders of magnitude of each other. For these same elements, crustal concentrations span more than 4 orders of magnitude. In general, toxicity thresholds decrease with decreasing crustal abundance (i.e., less abundant compounds are more toxic) until a bottom threshold is reached, at which point all compounds have more or less similar toxicity thresholds.

One might wonder why those elements that are less abundant would not have a correspondingly lower toxicity threshold. The answer seems to be related to enzyme kinetics and cellular function. First, the kinetics of nutrient uptake and assimilation involve complicated interactions of passive and active movement through cell walls, voids in plant tissues, and eventually across membranes (Epstein, 1972). Minimum concentrations are needed in some cases to induce the synthesis of enzymes that mediate movement across membranes. Once the enzymes are produced, minimum concentrations are needed to reach the binding affinity constant equilibrium level before the enzyme can function. Evolution has evidently selected for systems that fall within a relatively narrow concentration range. Second, the modes of action of toxicity involve disruption of electron flow, altered conformation of proteins, changing redox potential and other disruptions to biochemical functions. Each of these modes of action entails a disruption of the normal homeostatic condition of cells and tissues. Therefore, the levels of toxic substances must reach a critical threshold before sufficient injury can occur.

2.1.2 Persistence and Transformation

Natural elements, including metals, metalloids and many derivative inorganic substances, are an inherent part of all terrestrial systems. As such, these substances persist in the environment at some concentration for indefinite lengths of time. Biogeochemical

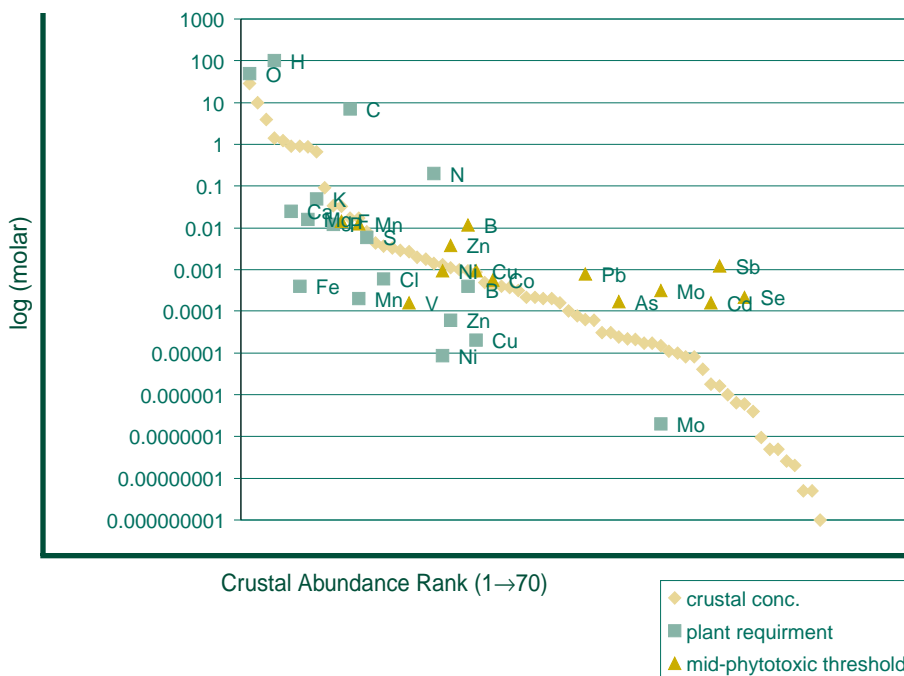


FIGURE 2. Log Crustal Concentration of the 70 Most Abundant Elements, Required Concentrations (ppm) for Plants, and Phytotoxic Levels Arranged in Descending Order of Crustal Abundance

cycling processes, often mediated by microbes, transform elemental moieties through the full range of valences proscribed for each element. Some forms are bioavailable, but others are virtually inaccessible to organisms. For hazard classification of commercial products, the relevant factors are: (1) how long the product persists in the environment; and, (2) whether the product or its derivative forms are bioavailable. The rate of transformation into or out of bioavailable states is of great importance. As in aquatic systems, *transformation* and *bioavailability* rather than *persistence* are more appropriate for hazard ranking in terrestrial systems.

Metals are made bioavailable to most soil organisms when they form a soluble, free-ion species in the soil pore water (Gunn et al., 1988). Site-specific soil parameters are very important in regulating this dissolution rate. Two of the most important soil parameters are pH and Cation Exchange Capacity (CEC). Complexation with ferrous ions or sulphides, the presence of other free metallic ions and binding with organic ligands also

influence transformation kinetics. Even though the role of these factors is well understood individually, their interaction is extremely complex.

For metals in particular, ionic forms and complexation products of the metal are very important in determining the potential of the metal for uptake by, and to cause toxicity in, soil organisms. Generally, the elemental form is less bioavailable than the free ionic forms (Checkai *et al.*, 1982). Sophisticated computer models such as GEOCHEM (Mattigod and Sposito, 1979) or SOILCHEM (Alloway, 1995) can approximate how much of the parent material will remain under steady-state conditions and estimate the percentage of other free ions and complexation products. This information could then be used to adjust the soil toxicity concentration for the parent compound in a standardized test soil and to identify potentially important transformation products for further testing. Because it takes many months to years for a metal added to a soil to reach a steady state and toxicity tests are usually conducted a few hours after the metal is added, the amount of parent compound in test soils is greater than that found in the environment. Therefore, the test overestimates the toxicity (i.e., produces a lower EC_{50}) than would actually happen in the environment. To be realistic, the EC_{50} should be adjusted upward to account for the fact that it would take more parent compound to cause the same result under steady-state field conditions. For example, if a parent compound were reduced to 60% parent and 40% other cations or anions, then an EC_{50} of 50 mg/kg-soil would have to be adjusted to 84 mg/kg-soil for the parent compound. In other words, it would take more parent compound to result in the same toxic response in the natural environment because a proportion of the parent compound would be changed to a different form.

Because site-specific soil characteristics may dramatically alter assumptions of steady-state dynamics, model predictions of percent transformation should be used only under standardized or default settings for hazard classification purposes. Extreme caution must be exercised in using the model outputs to estimate the bioavailable fraction for specific sites (e.g., when assessing risk). Slight changes in several model input parameters can dictate large shifts in the model predictions which generally correlate poorly with measured values at a specific site.

2.1.3 Bioaccumulation

Some species have evolved tolerance for high soil concentrations of the naturally occurring elements. Others concentrate elements in their tissues to levels that reduce their palatability to predators (e.g., selenium-accumulating plants are generally avoided by browsers such as deer, antelope or cattle). However, most metals and their derivatives usually do not accumulate or biomagnify in the terrestrial food-chain (US EPA, 1992). Notable exceptions occur with cadmium and zinc, where invertebrates can accumulate amounts up to 50 times higher than are found in plants and 10 to 20 times higher than in soil (e.g., Edwards and Bohlen, 1996). These levels are still significantly less than

those of synthetic organic compounds which may bioaccumulate by several orders of magnitude. Moreover, as in aquatic systems, the bioaccumulation factor (BAF)³ from soil to plants or invertebrates changes as the soil concentration changes. For essential elements, soil concentrations in the deficiency zone lead to active uptake of material resulting in relatively high BAFs, whereas at sufficient concentrations, these processes are suppressed resulting in BAFs approximately equal to 1. At higher concentrations, organisms either actively exclude the uptake of substances from the soil (resulting in very low BAFs) or sequester them in their tissues rendering them non-toxic (resulting in higher BAFs) (Baker, 1981). Eventually, a threshold is reached where these homeostatic mechanisms are overwhelmed and toxicity results. For non-essential elements, passive uptake by plants occurs at low soil concentrations and active exclusion occurs at high soil concentrations resulting in apparently high BAFs at low soil concentrations and low BAFs at high soil concentrations. However, it would be incorrect to infer that the high BAFs at low soil concentrations result in increased hazard to higher trophic level organisms because the resulting concentration in plant tissues is still low. Therefore, bioaccumulation (in particular, the BAF) should not be used as a modifier of hazard classification of metals, minerals and their derivative compounds in terrestrial systems.

2.2 Environmental Effects

The initial classification of metals and metal compounds based on crustal abundance is modified by the inherent toxicity of the materials of interest. This modification allows the classification scheme to account for differences in bioavailability and biological activity of different forms of the same element. For example, while all forms of copper are likely less hazardous than all forms of cadmium, elemental copper is less hazardous than copper sulfate and elemental cadmium is less hazardous than cadmium chloride. Thus, the relative toxicity of the various ionic forms of a metal or metalloid should be determined in standard toxicity bioassays in order to rank the compounds relative to each other's inherent toxicity.

2.2.1 Intrinsic Toxicity

The intrinsic toxicity of a substance is established by the *threshold concentration* and the slope of a dose-response relationship for a given toxicological end-point. A substance that causes a toxic effect at high doses is considered less toxic than one that causes a toxic effect at low doses. If the toxic response progresses rapidly from minor effects to

3 BAF relates the concentration in plant or animal tissue to that in all media to which the organism is exposed (e.g., water, food, soil, air). The term "Bioconcentration Factor" (BCF) specifically refers to concentration of material in the tissues of plants or animals compared to the concentration in the water and excludes uptake from food. Thus, BAF, while generally not used in aquatic systems, is a more inclusive term and is more applicable in terrestrial systems.

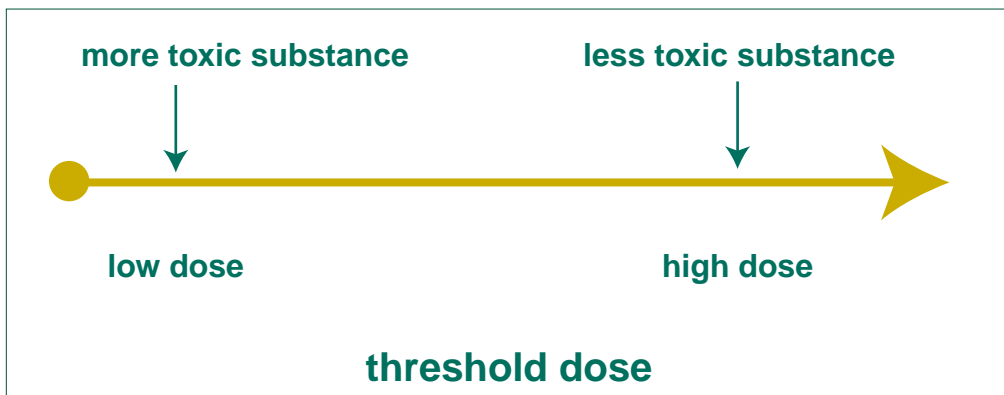


FIGURE 3.
Threshold Concentration

death as dose increases (i.e., the slope of the dose–response relationship is steep), organisms are considered less tolerant (or more sensitive) to the substance than if the toxic response progresses more slowly (Figures 3 and 4).

Therefore, when generating data for hazard classification, both the threshold value and the slope of the dose–response curve should be reported. We agree with the Nordic Working Group in recommending the use of an EC_{50} as the toxicity threshold value; that is, the concentration that causes the measured effect in 50% of the test organisms.⁴ In addition, we recommend a slope factor component to intrinsic toxicity, a component not included by the Nordic Working Group. The slope factor is the value of the dose–response slope calculated at the EC_{50} , provided all dose–response curves are developed by the same method (e.g., Probit Analysis). Alternatively, the slope factor is described as the percent increase in soil concentration required to change the response from an EC_{50} to an EC_{75} . The latter method avoids the problem of having dose–response relationships calculated by different statistical methods.

2.2.2 Test Species

In concert with the Nordic Working Group’s proposed classification system for synthetic organic substances, the system for metals and metal compounds proposed here will consider only the soil compartment of the terrestrial system. Following similar lines of reasoning, test organisms should include, at a minimum, representative species of plants, invertebrates and soil micro-organisms. Although some metals generally produce

⁴ Note that the “measured effect” can be mortality as well as non-lethal parameters such as growth rate or seed production.

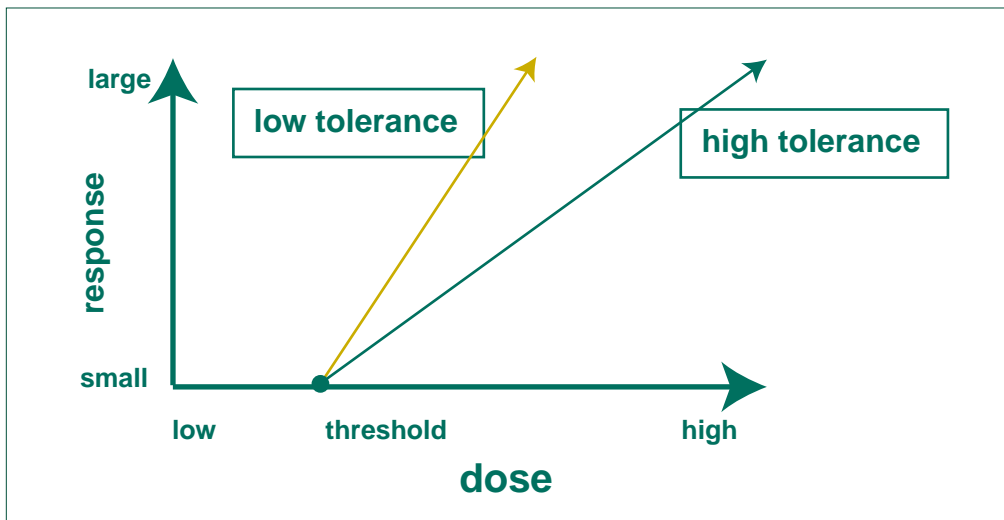


FIGURE 4.
Slope of Dose–Response Relationships

adverse effects only after prolonged (chronic) exposures, hazard classification is concerned mainly with potential short-term (acute and subchronic) effects as a result of human activities, modified for synthetic organic compounds by considering their potential to persist in the environment in a bioavailable form. The lettuce plant test suggested for toxicity testing under the proposed classification schemes for both synthetic organic and metal compounds extends over approximately one-quarter of the life span of the plant, including the important stages of seed germination and early seedling growth. For the earthworm test, the subchronic exposure period of a few weeks is sufficient to provide information about reproductive effects and potential mortality rates. Therefore, the classification system for naturally occurring metals and their derivatives will rely on acute and subchronic toxicity test data analogous to the synthetic organic chemical classifications in terrestrial and aquatic systems.

Ideally, hazard classification would be conducted using data from a range of species tested using standardized protocols. This procedure is particularly important for naturally occurring metals in terrestrial systems where the presence of other essential trace elements and nutrients in the soil can significantly alter the toxicity threshold and slope factors of the substance of interest. Although the literature contains a great deal of data on the response of plants to metals in the soil, particularly for the essential micronutrients, the data were not obtained using standard procedures needed for toxicity categorization or hazard classification. Therefore, we present a testing scheme using a few representative species in standardized tests, and suggest that published data should not be used.

2.2.2.1 Standard test species

We recommend several widely used species for standardized tests to augment hazard classification of metals in the soil environment (Table 3). Note that vertebrates (including fossorial animals such as moles, gophers and snakes) are not among those listed as they are considered part of the above-ground system.

It is important to remember that the standardized tests were developed for testing synthetic organic substances. Various aspects of the tests need to be adjusted for use with inorganic compounds (Fairbrother et al., 1996), particularly for the essential micronutrients. For the latter compounds, the test concentrations must all be above the amount required for adequate nutrition; non-essential elements and their derivatives can be tested at lower concentrations.

TABLE 3.

Recommended Species for Hazard Identification and Classification of Chemicals in the Soil Environment Using Standard Protocols

Species	Endpoints
Recommended species	
Plants	seedling growth; mortality
lettuce (<i>Lactuca sativa</i>)	
Soil Invertebrates	mortality; reproduction
earthworm (<i>Eisenia foetida</i>)	
Soil function	nitrification
soil microbes	
Alternative species	
Plants	seedling growth; mortality
perennial rye (<i>Lolium perenne</i>)	
alfalfa (<i>Medicago sativa</i>)	
Soil Invertebrates	mortality; reproduction
collembola (<i>Folsomia candida</i>)	
beetles (<i>Bembidion lampros</i>)	
nematode (<i>Steinernema sp.</i>)	
Soil function	respiration
soil microbes	

2.2.3 Data Quality Criteria

Attention should be paid to the adequacy and relevancy of data used for toxicity categorization in the hazard classification process. A large amount of data exists in the peer-reviewed literature, not all of which is useful in the toxicity categorization process as they were generated with other purposes in mind. While a detailed discussion of test methodology and quality assurance is not included in this document, we suggest that the data quality criteria described below be considered when developing appropriate toxicity tests or reviewing the existing literature for effects of metals and their derivatives on soil organisms.

Test conditions must be described appropriately, particularly if the test did not follow accepted standard protocols for determining the toxicity of metals to soil organisms. This includes a description of soil factors such as pH, percent clay and the amount of nitrogen, phosphorus and essential trace elements present, as well as other environmental factors such as temperature, humidity, and light intensity and duration. The test must have been performed within the optimal concentration range for essential elements. Both nominal (amount added) and actual (amount measured) concentrations of the test substance in the soil should be provided using acceptable analytical methods and procedures. In addition, the methods must specify whether total metals were measured or whether the soluble pore water fraction (the bioavailable portion) was analysed. The statistical validity of data analyses should be ascertained. A clear dose-response relationship should have been established, and the study must either report the EC₅₀ value or provide the data in a manner from which EC₅₀ values can be derived. This implies that an adequate number and distribution of soil concentrations of the test substance were used with appropriate replication at each concentration. Preference should be given to studies that provide sufficient information to calculate a slope factor for modifying the intrinsic toxicity categorization.

Thus, the fact that a study appears in the peer-reviewed scientific literature is insufficient qualification to use it in the hazard classification process. Once accepted standard protocols are available, the quality of existing data can be compared to the standard methods. Until then, the data quality categories described above should help guide the assessment of whether a study that was designed and conducted for a different purpose can provide information relevant to a generic hazard classification process for naturally occurring metals and their derivative substances.

CHAPTER 3

Combination of Properties to Form Criteria

Hazard classification of synthetic organic substances in aquatic or soil environments uses a two-step process. The intrinsic toxicity (defined as harmful, slightly toxic and very toxic in aquatic systems, or as toxic and very toxic in terrestrial environments) is modified by whether or not the compound is persistent and bioaccumulative. The process for classifying metals and their derivatives follows a similar logic through a three-stage process (Figure 5). Compounds are classified first, based on the natural crustal abundance of the element, and ranked as *Unclassified*, *Hazardous* or *Very Hazardous*.

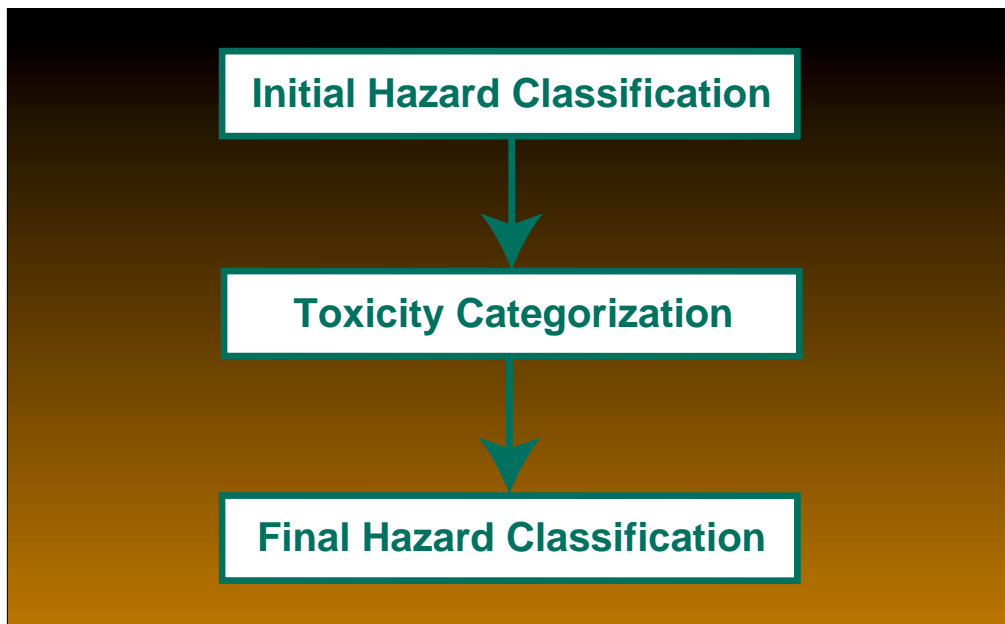


FIGURE 5.
Three-Stage Hazard Classification Process

This classification is modified by the intrinsic toxicity based on the lowest EC_{50} value determined from standard plant, earthworm and soil micro-organism bioassays, modified by the calculated percent parent product at steady state (cf. section 2.1.2). Toxicity categories include *Harmful*, *Toxic* and *Very Toxic*.⁵ Before application, the toxicity category is modified by the slope factor from the dose–response relationship (Figure 6).

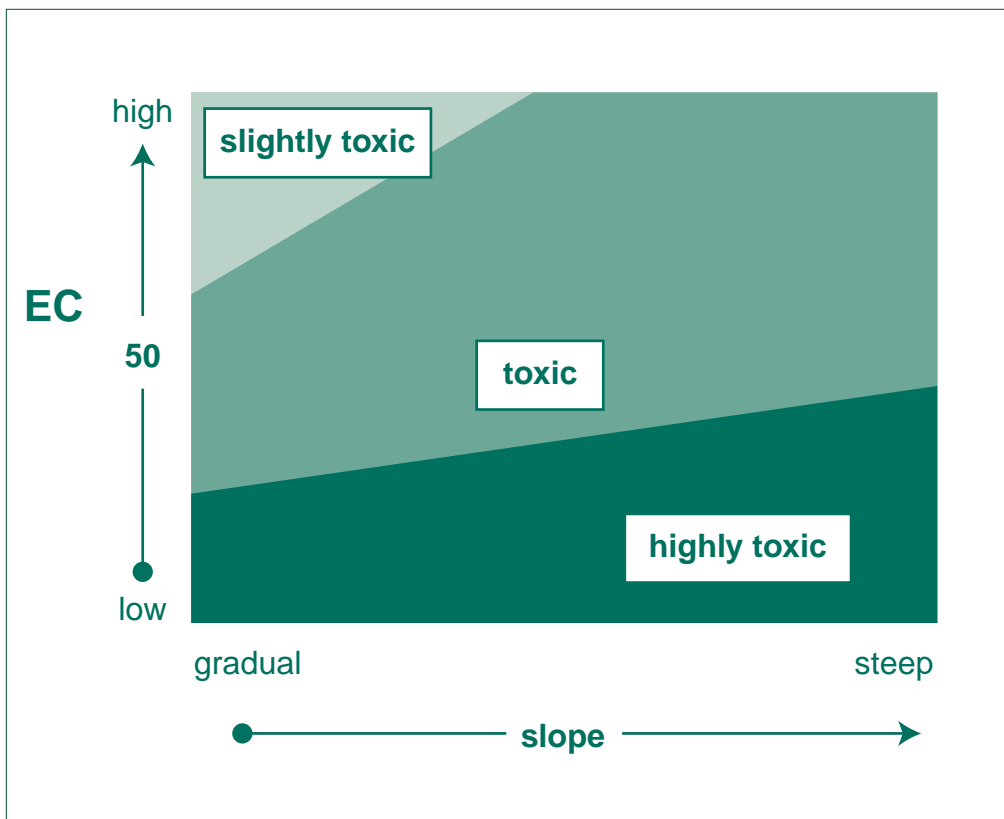


FIGURE 6.
Intrinsic Hazard Classification Based on Toxicity and Slope of Dose–Response Relationship

5 The category labels of “very toxic,” “toxic” and “harmful” follow standard OECD and European Union terminology. Note that the “harmful” category does not follow the popular definition of “harm” as it has no upper bound and, therefore, includes all substances which produce little to no response in soil organisms.

CHAPTER 4

Selection of Cut-Off Values

This section defines the suggested values (i.e., trigger limits) to use for each of the classification parameters to place a compound under investigation into the correct hazard category.

4.1 Crustal Abundance

Based on our earlier analysis of the relationship between crustal concentration, essentiality and phytotoxicity, we propose using crustal abundance for the initial hazard ranking of naturally occurring elements. Two “breaks” offer logical delineators of low, medium and high hazard. (1) The 10 most abundant elements (O, Si, Al, H, Na, Ca, Fe, Mg, K and Ti) generally are not considered toxic to terrestrial organisms (i.e., they have high toxicity thresholds, corresponding to their high crustal or atmospheric abundance). These would provisionally remain as *Unclassified*. (2) The elements ranked 11 through 30 occur at relatively high concentrations and have phytotoxic thresholds near the crustal concentration values. This group also contains nearly all of the essential elements. It would provisionally be classified as *Hazardous*. Elements ranked above 30 have phytotoxic thresholds above the respective crustal concentrations, and they occur at relatively low concentrations. In this group, the approximately linear relationship between crustal abundance and toxicity falls apart as crustal abundance continues to decrease but the toxicity thresholds remain constant. This is due to the processes discussed earlier (cf. section 2.1.1) which require that the levels of toxic substances must reach a critical threshold before injury can occur. The last group would be provisionally ranked as *Very Hazardous*. That is:

<i>Unclassified:</i>	crustal abundance rank ≤ 10
<i>Hazardous:</i>	$11 \leq$ crustal abundance rank ≤ 30
<i>Very Hazardous:</i>	crustal abundance rank ≥ 31

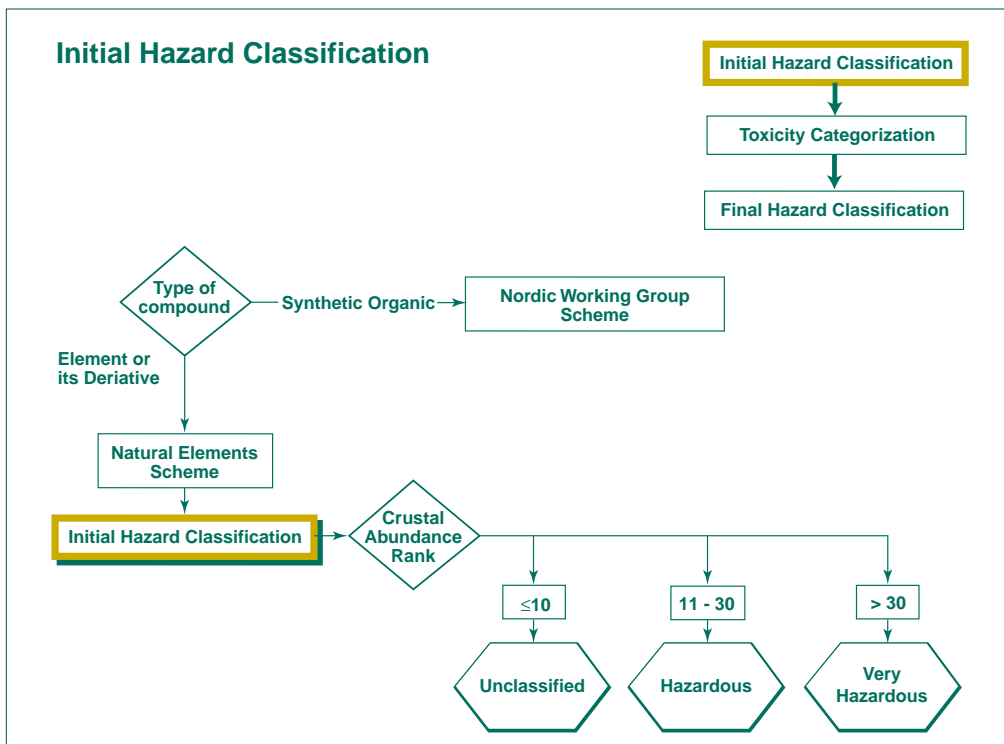


FIGURE 7.
Initial Hazard Classification Flow Chart

4.2 Toxicity

Toxicity categorization must begin by determining whether or not the element of concern is essential to plants or animals. If it is not, the hazard classification proceeds in a straightforward manner to determine toxicity and apply the cut-off values described below. If it is an essential element, the range for optimal functioning of the organism and the toxic concentration must be considered (Figure 8, Tables 4 and 5). For an EC_{50} to be acceptable for hazard classification purposes, it must be derived from an acceptable study whose lowest concentration is above the nutrient requirements for plants or animals. Otherwise, any adverse effects of the element might be confused with symptoms of deficiency.

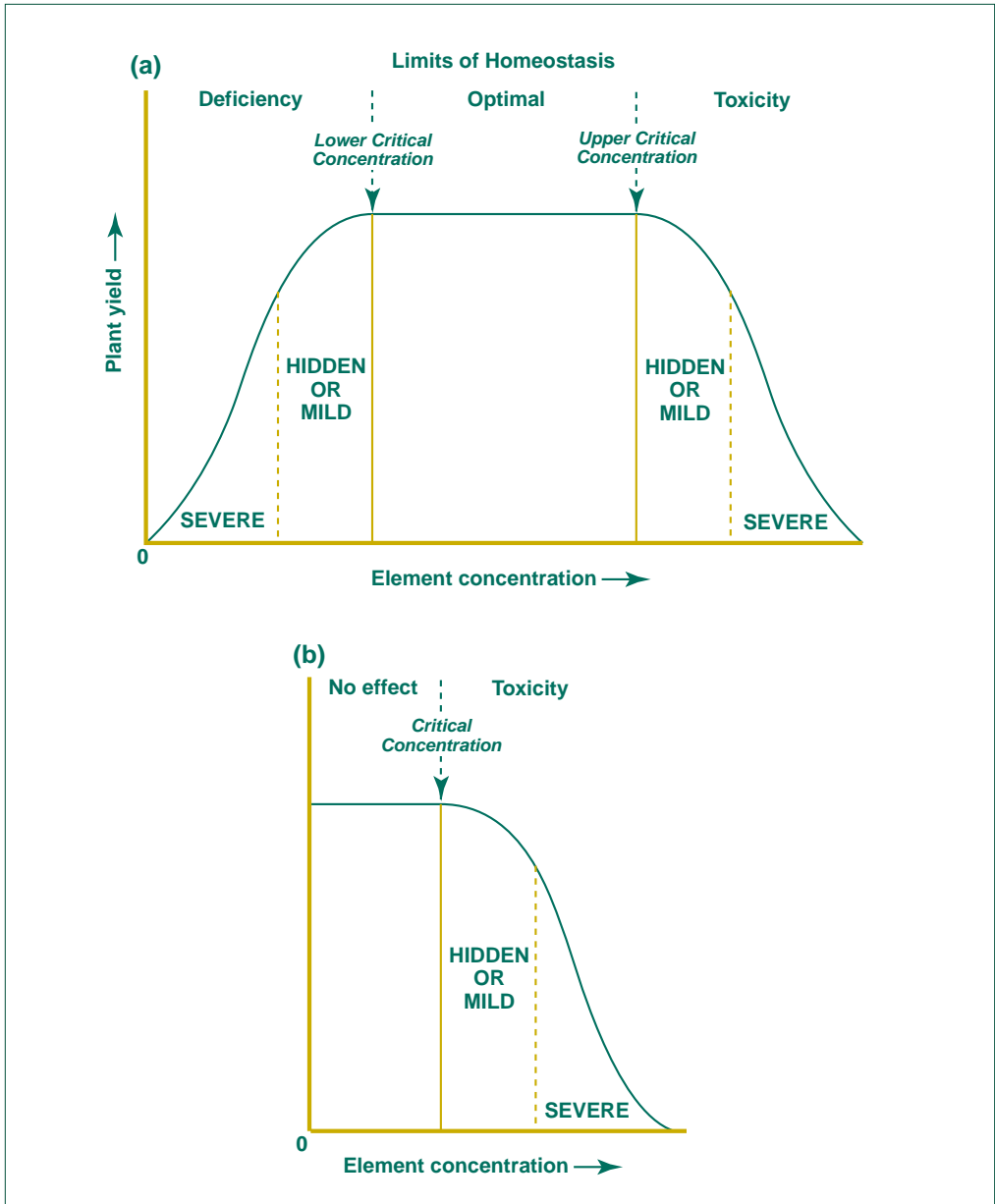


FIGURE 8. Typical Dose-Response Curve for: (a) Essential Elements; and, (b) Non-Essential Elements (Alloway, 1995)

TABLE 4.
Generalized Elemental Requirements (mg/kg soil) of Plants

element	solution *	soil solution **	exchange complex **
B	4	0.1 – 6	very low
Ca	1000	50 – 1000	500 – 2000
Cl	22	10 – 1000	0
Cu	1.27	0.01	10 – 1000
Fe	22	0.1 – 25	1 – 500
Mg	389	1 – 100	20 – 50
Mn	11	0.2 – 2	1 – 4000
Mo	0.02	<0.001	low
Ni	0.50	n. r.	n. r.
P	372	0.001 – 20	10 – 1000
K	1955	1 – 50	10 – 50
S	192	3 – 5000	low
Zn	4	0.1 – 0.3	3 – 20

* calculated from McClendon (1976)

** Bidwell (1979)

n. r. = not reported

TABLE 5.
Trace Element Effects Concentrations (mg/kg soil) for Plants

element	sensitive plants – toxic range	element	sensitive plants – toxic range
Ag	5 – 10	Mo	10 – 50
As	5 – 20	Ni	10 – 100
B	50 – 200	Pb	30 – 300
Ba	500	Sb	150
Be	10 – 50	Se	5 – 30
Cd	5 – 30	Sn	60
Co	10 – 20	Ti	50 – 200
Cu	15 – 20	Tl	20
F	1 – 3	V	5 – 10
Hg	0.5 – 1	Zn	100 – 400
Li	5 – 50	Zr	15
Mn	400 – 1000		

Source: Kabata-Pendias and Pendias (1992)

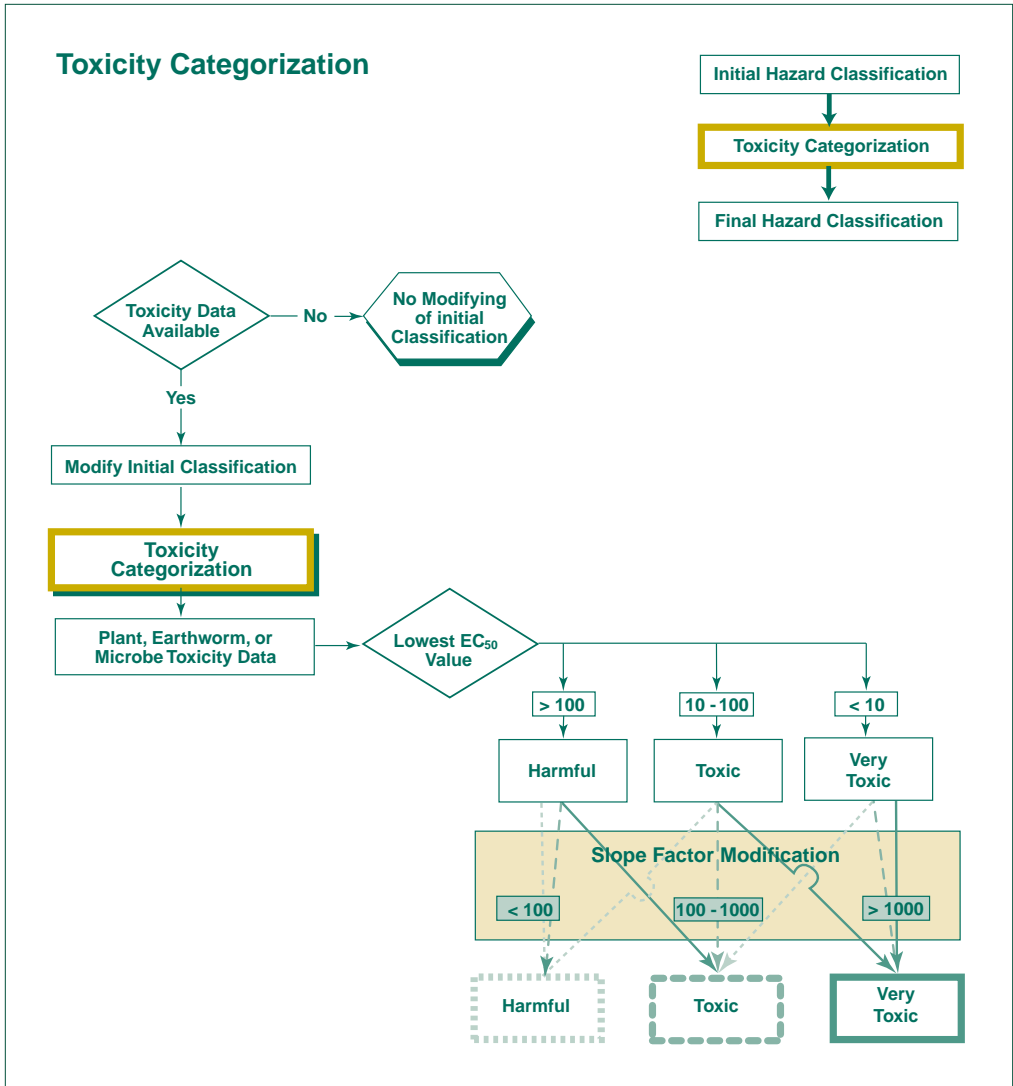


FIGURE 9.
Toxicity Classification Scheme Flow Chart

4.2.1 Toxicity to Soil Organisms

Recommendations for cut-off levels for toxicity of metals to soil organisms are based on the data and values generated by the Nordic Working Group for synthetic organic compounds as well as on a review of the phytotoxicity data for metals (Kabata-Pendias and Pendias, 1992). Most phytotoxicity values for naturally occurring elements fall within two orders of magnitude of each other. In addition, the cut-off values recommended by the Nordic Working Group for synthetic organic compounds appear satisfactory for naturally occurring elements and can be adopted as follows:

<i>Very Toxic:</i>	EC ₅₀ values	≤10 mg/kg soil
<i>Toxic:</i>	EC ₅₀ values	10<X≤100 mg/kg soil
<i>Harmful:</i>	EC ₅₀ values	>100 mg/kg soil

The EC₅₀ value used above is the lowest value from among the standard soil bioassay tests for a plant, an earthworm and a soil micro-organism (see Table 3), regardless of end-point and after it has been adjusted for the percent parent compound in the soil at equilibrium (cf. section 2.1.2).

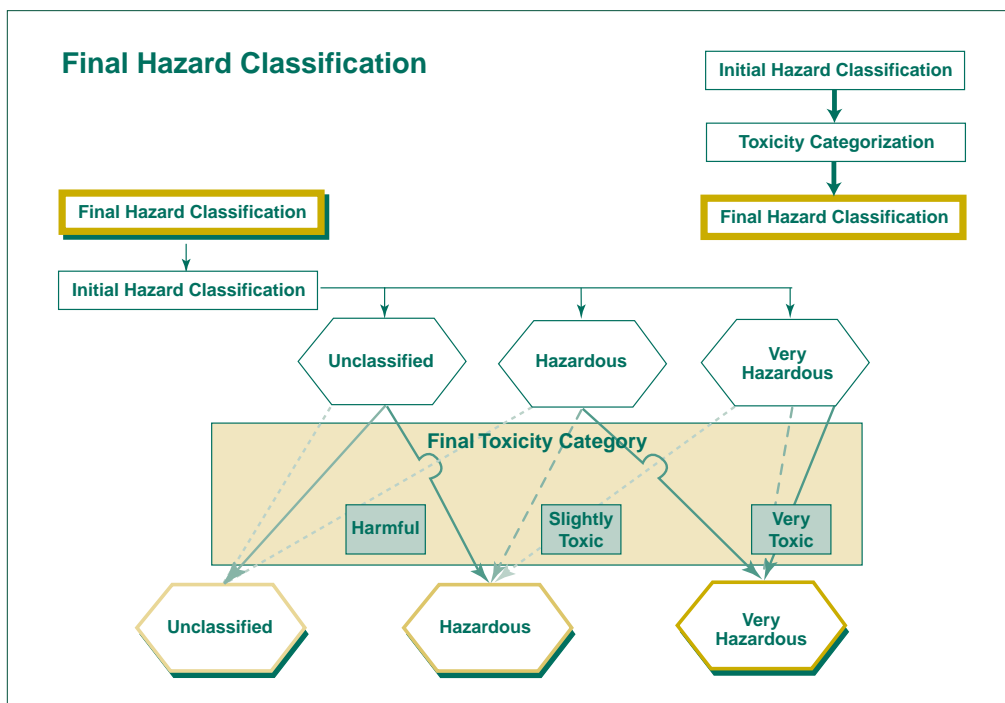


FIGURE 10.
Final Hazard Classification Scheme Flow Chart

4.2.2 Slope Factor

Cut-off values for the slope factor modification of the EC₅₀ toxicity ranking were developed from a comparative study of earthworm toxicity data in Callahan et al. (1994), soil respiration effects in Shirazi et al. (1984), and general phytotoxicity data. The term “slope factor” is defined as the amount of increase in soil concentration necessary to move from the EC₅₀ to the EC₇₅ in the standard test used to set the toxicity value. We recommend the following cut-off values:

adjust toxicity *down* one category if: slope factor ≤ 100
do not adjust toxicity category if: $100 < \text{slope factor} \leq 1000$
adjust toxicity *up* one category if: slope factor > 1000

4.3 Final Hazard Classification

Once the toxicity category has been determined from the EC₅₀ as modified by the transformation percentage and slope factor, the initial hazard classification based on crustal abundance rank is reviewed. Hazard classification is revised according to the following toxicity category assignments:

Harmful: Unclassified \longrightarrow No change
 Hazardous \longrightarrow Unclassified
 Very Hazardous \longrightarrow Hazardous

Toxic: Unclassified \longrightarrow Hazardous
 Hazardous \longrightarrow No change
 Very Hazardous \longrightarrow Hazardous

Very Toxic: Unclassified \longrightarrow Hazardous
 Hazardous \longrightarrow Very Hazardous
 Very Hazardous \longrightarrow No change

CHAPTER 5

Conclusion

The proposed hazard classification scheme presented here has several attractive features for both regulatory bodies and industry. First, and most importantly, by relying on elemental crustal abundance for the initial classification, the whole family of commercial products can be classified from the outset. The elements and their derivatives that lie near the cut-off lines would be the ones most likely to warrant special attention. Second, if either industry or regulators felt concern over the initial classification, a set of discrete steps is offered to incorporate toxicity and transformation information into the process.

The use of crustal abundance as the starting point draws upon a large body of biological research dating back to the mid-1800s when efforts were focused on determining nutritional requirements for plants and animals. Extensive work done in this century in plant and animal physiology formed the basis of McClendon's (1976) analysis of crustal abundance and nutritional requirements. The measure of crustal abundance represents the total amount of an element in the crust, which is substantially greater than the bioavailable fraction. Thus, crustal abundance concentrations represent a conservative position (i.e., margin of protection) for use in hazard classification.

Implementation of this approach could be immediate, requiring no new data. To achieve the toxicity modification and final hazard ranking, consensus on two standard guidelines would be needed:

- a. standard toxicity testing parameters; and,
- b. default settings for GEOCHEM or an equivalent predictive transformation model.

Finally, the proposed approach is conceptually similar to the hazard-ranking approach for synthetic organic compounds. The two aspects of hazard ranking would therefore be compatible in a regulatory sense and would reflect the unique properties of naturally occurring substances.

CHAPTER 6

References

- Alloway, B. J. 1995. *Heavy Metals in Soils*. Second Edition. Chapman & Hall, New York, NY. p. 31.
- Baker, A. J. M. 1981. Accumulators and excluders – strategies in the response of plants to heavy metals. *J. Plant Nutr.* 3: 643–654.
- Bidwell, R. G. S. 1979. *Plant Physiology*. Second Edition. Macmillan Publishing Co., New York, NY.
- Callahan, C. A., M. A. Shirazi, and E. F. Neuhauser. 1994. Comparative toxicity of chemicals to earthworms. *Environ. Toxicol. Chem.* 13: 291–298.
- Checkai, R. T., R. B. Corey, and P. A. Helmke. 1982. The effects of ionic and complexed Cd on metal uptake by plants. *Agron. Abstr. Amer. Soc. Agron.*, Madison, WI.
- Edwards, C. A., and P. J. Bohlen. 1996. *Biology and Ecology of Earthworms*. Third Edition. Chapman & Hall, London.
- Epstein, E. 1972. *Mineral Nutrition of Plants: Principles and Perspectives*. Wiley, New York, NY.
- Fairbrother, A., L. A. Kapustka, I. Thornton, and W. H. O. Ernst. 1996. *Review of Terrestrial Toxicity Testing: With Particular Emphasis on Issues Affecting Validity and Efficacy of Tests for Metal Compounds*. Prepared for International Lead Zinc Research Organization, Research Triangle Park, NC.
- Gunn, A. M., D. A. Winnard, and D. T. E. Hunt. 1988. Trace metal speciation in sediments and soils: An overview from a water industry perspective. Pages 261–275 in Kramer, J. R. and H. E. Allen, eds. *Metal Speciation: Theory, Analysis and Applications*. Lewis Publishers Inc., Chelsea, MI.
- Kabata-Pendias, A., and H. Pendias. 1992. *Trace Elements in Soils and Plants*. Second Edition. CRC Press, Inc., Boca Raton, FL.

Mattigod, S. V., and G. Sposito. 1979. Chemical modeling of trace metal equilibria in contaminated soil solutions using the computer program GEOCHEM. Pages 837–856 in Jenne, E. A., ed. *Chemical Modeling in Aqueous Systems*. ACS Symposium Series 93. American Chemical Society, Washington, DC.

McClendon, J. H. 1976. Elemental abundance as a factor in the origins of mineral nutrient requirements. *J. Mol. Evol.* 8: 175–195.

National Academy of Science (NAS). 1983. *Risk Assessment in the Federal Government: Managing the Process*. National Academy Press, Washington, DC.

National Research Council (NRC). 1980. *Mineral Tolerances of Domestic Animals*. National Academy Press, Washington, DC.

Plaa, G. L. 1989. Introduction to toxicology: Occupational and environmental toxicology. In Katzgun, B. B., ed. *Basic and Clinical Pharmacology*. Fourth Edition. Lang Publishers, Los Altos, CA.

Shirazi, M. A., B. Lighthart, and J. Gillett. 1984. A method for scaling biological response of soil microcosms. *Ecological Modeling*. 23: 203–226.

Skujins, J. 1987. Essential nutrient elements and nutrient cycles in soil. Pages 41–47 in Wilson, K. G. and D. W. Newman, eds. *Models in Plant Physiology and Biochemistry, Volume III*. CRC Press, Boca Raton, FL.

US Environmental Protection Agency (US EPA). 1992. *Technical Support Document for Land Application of Sewage Sludge*. US Environmental Protection Agency, Office of Water, November 1992.

NOTES

NOTES

About the Authors

Anne Fairbrother

Anne Fairbrother, D.V.M., Ph.D., is Senior Wildlife Ecotoxicologist and Certified Wildlife Biologist with Ecological Planning and Toxicology, Inc., Corvallis, Oregon, USA, and holds an adjunct professorship at College of Veterinary Medicine of Oregon State University. Before joining the private sector, she worked as Senior Scientist for the US EPA. She has published over 50 peer-reviewed articles, books and book chapters on wildlife ecotoxicology and environmental risk assessment. Dr. Fairbrother has served on numerous advisory committees, including the Advisory Panel on Ecotoxicity of the International Lead Zinc Research Organization, the Nickel Producers' Environmental Research Association and the International Copper Association, the Science Advisory Committee of the US EPA's Center of Excellence in Ecotoxicology at the University of California, Davis, and the National Research Council Committee on Animals as Sentinels of Environmental Health Hazards. She was President of the Wildlife Disease Association from 1995 to 1997, has been an active member of the Society of Environmental Toxicology and Chemistry and has participated in five Pellston Workshops on various aspects of ecological risk assessment. Dr. Fairbrother serves as Associate Editor for the *Journal of Wildlife Management*, and on the editorial boards of the *Journal of Wildlife Diseases* and *Environmental Toxicology and Chemistry*.

Lawrence A. Kapustka

Lawrence A. Kapustka, Ph.D., is President and Senior Ecotoxicologist at Ecological Planning and Toxicology, Inc., Corvallis, Oregon, USA. Before joining the private sector, Dr. Kapustka was Professor of Botany at Miami University, Ohio, and Senior Scientist at the US EPA. Dr. Kapustka has written over 50 peer-reviewed articles and book chapters on plant ecotoxicology and environmental risk assessment. He has delivered scientific seminars and technical papers throughout the USA, as well as in Canada, China, England, Hungary, Poland, Sweden and Yugoslavia. Dr. Kapustka is a Certified Senior Ecologist and Environmental Specialist. He has served on the Ecological Risk Assessment Advisory Group of the Society of Environmental Toxicology and Chemistry; as a Liaison Member of the Pacific Northwest Council of the President's Council on Sustainable Development; as President of the Pacific Northwest Chapter of the Society of Environmental Toxicology and Chemistry; as Chair of the American Society for Testing and Materials Subcommittees on Wildlife Toxicology (E47.04) and Biological Field Methods (E47.08); as an active member of the Subcommittees on Plant Toxicology (E47.11) and Risk Assessment (E47.13); as a member of the Executive Committee of ASTM E47 Biological Effects and Environmental Fate; as a member of the Standard Methods Committee for the Water Environment Federation; and, as a World Trade Mission Delegate, 22nd General Assembly, Budapest, Hungary.