ES/ER/TM-85/R3

# Toxicological Benchmarks for Screening Contaminants of Potential Concern for Effects on Terrestrial Plants: 1997 Revision

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Date Issued—November 1997

Prepared for the
U.S. Department of Energy
Office of Environmental Management
under budget and reporting code EW 20

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for the
U.S. DEPARTMENT OF ENERGY

# PREFACE

The purpose of this technical memorandum is to present plant toxicity data and discuss their utility as benchmarks for determining the hazard to terrestrial plants caused by contaminants in soil. This work was performed under Work Breakdown Structure 1.4.12.2.3.04.07.02 (Activity Data Sheet 8304). This report presents a standard method for deriving benchmarks, a set of data concerning effects of chemicals in soil or soil solution on plants, and a set of phytotoxicity benchmarks for 38 chemicals potentially associated with United States Department of Energy sites. In addition, background information on the phytotoxicity and occurrence of the chemicals in soils is presented, and literature describing the experiments from which data were drawn for benchmark derivation is reviewed.

# ACKNOWLEDGMENTS

The authors would like to thank the following individuals for their helpful reviews of the document: Richard Bonczek, Jeffrey Duncan, Ruth Hull, David Kocher, Bobette Nourse, Dennis Opresko, Mark Stack, and Barbara Walton. Parts of the literature review for this report were conducted by Melanie Futrell and Christopher Evans.

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# ABBREVIATIONS

| | |
|---|---|
| CCME | Canadian Council of Ministers of the Environment |
| CEC | Cation Exchange Capacity |
| CERCLA | Comprehensive Environmental Response, Compensation, and Liability Act |
| DNA | Deoxyribonucleic Acid |
| DOE | United States Department of Energy |
| EIV | Ecotoxicological Intervention Value |
| EPA | United States Environmental Protection Agency |
| ER-L | Effects Range Low |
| LCT | Lowest Concentration Tested |
| LOEC | Lowest Observed Effect Concentration |
| NOEC | No Observed Effect Concentration |
| ORR | Oak Ridge Reservation |
| PAH | Polyaromatic Hydrocarbon |
| PCB | Polychlorinated Biphenyl |
| RC | Remediation Criteria |
| RIVM | National Institute of Public Health and Environmental Protection |
| USGS | United States Geologic Survey |

# EXECUTIVE SUMMARY

One of the initial stages in ecological risk assessment for hazardous waste sites is screening contaminants to determine which of them are worthy of further consideration as contaminants of potential concern. This process is termed contaminant screening. It is performed by comparing measured ambient concentrations of chemicals to benchmark concentrations. Currently, no standard benchmark concentrations exist for assessing contaminants in soil with respect to their toxicity to plants.

This report presents a standard method for deriving benchmarks for this purpose (phytotoxicity benchmarks), a set of data concerning effects of chemicals in soil or soil solution on plants, and a set of phytotoxicity benchmarks for 38 chemicals potentially associated with United States Department of Energy (DOE) sites. In addition, background information on the phytotoxicity and occurrence of the chemicals in soils is presented, and literature describing the experiments from which data were drawn for benchmark derivation is reviewed. Chemicals that are found in soil at concentrations exceeding both the phytotoxicity benchmark and the background concentration for the soil type should be considered contaminants of potential concern.

# 1. INTRODUCTION

## 1.1 SCREENING BENCHMARKS IN ECOLOGICAL RISK ASSESSMENT

An important step in ecological risk assessment is screening the chemicals occurring on a site for contaminants of potential concern. Screening may be accomplished by comparing reported concentrations in media to a set of toxicological benchmarks. Multiple endpoints have been established for assessment of risks posed by soil-borne contaminants to organisms directly impacted by them. This report supersedes a prior report on screening benchmarks for phytotoxicity (Will and Suter 1995a). Benchmarks for toxic effects of contaminants on earthworms and soil microbial processes are presented in a companion report (Will and Suter 1995b), which will also be revised in 1997.

If a chemical concentration or the reported detection limit exceeds the screening benchmark, more analysis is needed to determine the hazards posed by that chemical (i.e., it is a contaminant of potential concern). If, however, the chemical concentration or its detection limit falls below the proposed benchmark, the chemical may be ignored during further study unless public concern or ancillary evidence suggest that it should be retained.

The purpose of this report is to present plant toxicity data and to use them to derive benchmarks for determining the hazard to terrestrial plants caused by contaminants in soil. Benchmarks are provided for soils and solutions.

Tests of the toxicity of chemicals in the rooting medium of plants are conducted using a variety of rooting media which have been divided into two categories for purposes of this report: soil and solution. In a previous version of this document, data from experiments conducted in other growth media were provided, such as vermiculite and quartz sand. However, these data were determined to be not applicable to field situations and were not used in benchmark derivation; therefore, these data have been omitted from the present revision of the document.

Tests conducted in natural soils (even when brought into the laboratory, dried, sieved, fertilized, etc.) are assumed to be representative of the exposure of plants to contaminants measured in field soils. Tests conducted in nutrient and mineral solutions are assumed to be representative of exposures of plants to contaminants measured in soil solutions (e.g., from lysimeter samples or possibly from aqueous extracts of soil) or in very shallow groundwater (e.g., plants in the vicinity of seeps and springs).

Soil benchmarks are based on data provided by toxicity studies in the field or more commonly in greenhouse and growth chamber settings. Most of the soil concentrations of metals reported from waste sites are from extractions with hydrochloric acid or other mineral acids which are intended to provide total concentrations. Similarly, concentrations of organic contaminants in waste site soils are total concentrations derived from rigorous solvent extractions. In some cases, toxicity tests report concentrations extracted from contaminated soils, but various extractants are used that may not yield total concentrations. More commonly, the concentrations reported are nominal concentrations of a soluble form (i.e., a highly bioavailable form) of the chemical added to soil. Most metals in natural soils and contaminants of waste sites are in poorly available forms.

Solution benchmarks include data from toxicity tests conducted using whole plants rooted in aqueous solutions. Tests are commonly conducted in this manner because plants are assumed to be exposed to contaminants in the solution phase of soil, and the presence of soil in test systems reduces the experimenter's degree of control over exposure. Groundwater samples from waste sites are typically acidified before analysis to obtain total concentrations, but some samples are filtered before acidification. In general, the concentrations in filtered samples are likely to be more comparable to the concentrations reported from solution toxicity tests and should be used if available.

These benchmarks are to serve primarily for contaminant screening. An assessor must realize that the soil and plant characteristics discussed in the following sections play a large part in plant toxicity and incorporate these site-specific considerations in the evaluation of the potential hazards of a chemical. If chemical concentrations reported in field soils that support vigorous and diverse plant communities exceed one or more of the benchmarks presented in this report or if a benchmark is exceeded by background soil concentrations, it is generally safe to assume that the benchmark is a poor measure of risk to the plant community at that site.

## 1.2 CHEMICALS IN THE SOIL-PLANT SYSTEM

Elements occur in the soil in a variety of forms more or less available for uptake by plants. Many of the contaminants of concern at waste sites are metals or metalloids. Availability is determined by characteristics of the elements, such as behavior of the ion as a Lewis acid (electron acceptor) which determines the predominant type and strength of bond created (ionic or covalent) and, therefore, the mobility of the metal in the soil environment. Soil characteristics (e.g., pH, clay and organic matter content and type, and moisture content) also determine availability to plants by controlling speciation of the element, temporary immobilization by particle surfaces (adsorption-desorption processes), precipitation reactions, and availability in soil solution. The most general sinks for metals are iron and manganese oxides and organic matter (Jenne and Luoma 1977). Although particulate soil organic matter serves to immobilize metals, soluble organic matter may act to keep metals in solution in a form absorbed and translocated by plants.

The final control on availability of metals and metalloids in soil to plants is the selective absorption from soil solution by the root. Metals may be bound to exterior exchange sites on the root and not actually taken up. They may enter the root passively in organic or inorganic complexes with the mass flow of water or actively by way of metabolically controlled membrane transport systems often meant to take up a nutrient which the "contaminant" metal mimics. At different soil solute concentrations, metals may be absorbed by both processes. Absorption mechanisms and quantity absorbed are influenced by plant species (and cultivar), growth stage, physiological state, and the presence of other elements.

Once in the plant, a metal can be sequestered in the roots in vacuoles or in association with cell walls and organelles or translocated to above ground parts in xylem as organic or inorganic complexes. Location and forms of metals in plants, as well as their toxic effects, depend on plant species, growth stage, physiological state, and presence of other metals.

Mechanisms of toxicity of metals tend to be dependent on the nature of the reactivity of the metal itself. They may alter or inhibit enzyme activity, interfere with deoxyribonucleic acid (DNA) synthesis or electron transport, or block uptake of essential elements. Variability in response to `toxic' levels of metals by different plants is due to a number of defenses. These include exclusion from the root, translocation in nontoxic form, sequestering in nontoxic form in the root or other plant parts, and formation of unusable complexes containing metals that may otherwise be inserted into biomolecules instead of the proper element (e.g., As replacing P) (Peterson, 1983).

Organic compounds of environmental concern include nonionic compounds [pyrene, chlorinated benzenes, polychlorinated biphenyls (PCBs), toluene, and many pesticides], ionizable compounds (chlorophenols, carboxylic acids, surfactants, and amines), and weakly hydrophobic volatile organic compounds (trichloroethene). For the nonionic compounds, sorption in soil is mainly a function of degree of hydrophobicity and amount of sorbent hydrophobic phase (i.e., soil organic matter). Sorption of the compound by soil organic matter is reversible. The activities of these compounds in soil can be predicted by the organic matter-water coefficient, $K_{om}$, as estimated by the octanol-water coefficient, $K_{ow}$. Absorption onto colloidal organic matter in solution may alter the availability of these nonionic compounds. Ionizable compounds contain anionic or cationic moieties or both within their structure. These charged structures interact with organic and inorganic charged surfaces in the soil in a variety of reversible reactions. The extent and nature of the associations with charged surfaces depends on characteristics of the organic compound, solution pH and ionic strength, and mineral composition of the soil particulates (Schwarzenbach et al. 1993). Organic compounds may be degraded by microorganisms in the soil to metabolites with greater or lesser toxicity. Very stable compounds, like highly chlorinated PCBs, may persist in essentially unaltered form for many years.

Plant roots are not discriminating in uptake of small organic molecules (molecular weight less than 500) except on the basis of polarity. More water soluble molecules pass through the root epidermis and translocate throughout the plant. The less soluble compounds (like many polycyclic aromatic hydrocarbons) seem to have limited entry into the plant and minimal translocation once inside. Highly lipophilic compounds, such as PCBs, move into the plant root via the symplastic route (from cell to cell, as opposed to between the cells) and are translocated within the plant.

# 2. METHODS

## 2.1 DATA

References on the toxicity of selected chemicals to terrestrial plants were obtained from searches of bibliographic databases (BIOSIS, POL TOX I, current contents), a numeric database (PHYTOTOX), review articles, and conventional literature searches. Reports of toxicity tests of individual chemicals in laboratory, greenhouse, or field settings were obtained.

Data presented in this report were derived mainly from primary sources. Secondary sources were used if the primary source cited in the secondary source was unavailable, if only a small amount of data for a particular chemical was available, and if secondary sources suggested that a benchmark derived from limited primary source material was too high. The general criteria for inclusion of a study in the data set used to derive phytotoxicity benchmarks were:

1. if the methodology was clearly stated (especially concentrations of applied chemicals) and followed in the experiment,

2. if results were quantified as measures of plant growth or yield (e.g., weight, height) (measures of metabolic activity or tissue chemical concentration were used if measures of growth or yield were not available for a particular chemical of interest),

3. if results were presented in numeric form or graphical presentations of data were clearly interpretable, and

4. if an unambiguous reduction existed in the measured parameter within the range of applied concentrations of the chemical of interest.

The data selected for soil benchmarks are given in Appendix A. They were selected using these criteria and were assigned to the following categories for analysis:

1. Chemical—The effects of individual chemicals of interest were analyzed. In the case of metals, the metal is listed in the "Chemical" field. For organics, the compound is listed in the "Chemical" field.

2. Chemical Form—The form in which the chemical was added to the experimental medium.

3. Soil Type—Soil textural classification, if provided.

4. Cation exchange capacity (CEC) is the sum of the exchangeable cations that a soil can adsorb, expressed as milliequivalents per 100 g soil. Soil organic and inorganic constituents contain negatively charged sites that are the location of important interactions with positively charged ions in soil solution. These interactions partially control the effective toxicity of many contaminants.

5. Organic matter—Soil organic matter is important in reactions of many contaminants in the soil. Percentage organic carbon, if given, was converted to the more frequently cited measure of percentage organic matter by the equation (Nelson and Sommers 1982):

$$\%\text{organic carbon} \times 2 = \%\text{organic matter}$$

6. Soil pH—The pH of the soil system is a critical controller of the reactions occurring in the soil and therefore of the toxicity of any given quantity of chemical in the soil-plant system.

7. Plant Species—The analysis was limited to terrestrial vascular plants. Common names are given.

8. Exposure duration—The durations of exposure of the test plants to chemicals of interest ranged from 2 to 335 days, with trees generally being exposed longer than plants with shorter life spans.

9. NOEC Applied—The no observed effect concentration (NOEC) is defined herein as the highest applied concentration of the chemical of interest which gave a reduction of 20% or less in a measured response.

10. LOEC Applied—The lowest observed effect concentration (LOEC) is defined herein as the lowest applied concentration of the chemical of interest which gave a greater than 20% reduction in a measured response. In some cases, the LOEC for the test was the lowest concentration tested (LCT) or the only concentration reported, as when the $EC_{50}$ was reported.

11. Growth parameter—The majority of the growth responses were oven-dry weights of whole plants or their parts. Others included root length, plant height, relative growth rate, grain yield, seeds per plant, percent seed germination, and fresh and air-dry weights. Responses other than these growth and yield parameters were included only if growth or yield parameters were unavailable for a chemical.

The data selected for solution benchmarks using these criteria were assigned to the same categories for analysis with several exceptions. Categories relating to soil characteristics (type, CEC, % organic matter) were not applicable. These data are presented in Appendix B.

## 2.2 SELECTION OF TYPES AND LEVELS OF EFFECTS

Growth and yield parameters were used for two reasons. First, they are the most common class of response parameters reported from phytotoxicity studies; thus, they permit derivation of reasonably consistent benchmarks for a large number of contaminants. Second, growth and yield are ecologically significant responses both in terms of the plant populations and the ability of the vegetation to support higher trophic levels.

Twenty percent reduction in growth or yield was used as the threshold for significant effects to be consistent with other screening benchmarks for ecological risk assessment and with current regulatory practice (Suter et al. 1995). In brief, most regulatory criteria are based on concentrations in toxicity tests that cause effects which are statistically significantly different from controls. On average, those concentrations correspond to greater than a 20% difference in effects. In addition, regulatory actions may be based on comparisons of biological parameters measured on contaminated sites to those from reference sites. Differences between parameters at sites generally must be greater than 20% to be reliably detected in such studies. Therefore, the 20% effects level is treated as a conservative approximation of the threshold for regulatory concern.

## 2.3 DERIVATION OF BENCHMARKS

Because of the diversity of soils, plant species, chemical forms, and test procedures, it is not possible to estimate concentrations that would constitute thresholds for toxic effects on the plant communities at particular sites from published toxicity data. This situation is analogous to the problem of deriving benchmarks for sediments. In this report, the method used for deriving soil benchmarks is based on the National Oceanographic and Atmospheric Administration's method for deriving the Effects Range Low (ER-L) (Long and Morgan 1990), which has been recommended as a sediment screening benchmark by the United States Environmental Protection Agency (EPA) Region IV. The ER-L is the 10th percentile of the distribution of various toxic effects thresholds for various organisms in sediments.

This approach can be justified by assuming that the phytotoxicity of a chemical in soil is a random variate, the toxicity of contaminated soil at a particular site is drawn from the same distribution, and the assessor should be 90% certain of protecting plants growing in the site soil. Any bias in the data set would mitigate against that assumption. In this implementation of the approach, the bias most likely to be significant is the use of soluble metal salts in the toxicity tests. These salts are likely to be more toxic than the mixture of forms encountered in field soils. That bias would result in conservative benchmark values. Other possible sources of bias include the exclusion of synergistic and antagonistic effects resulting from interactions between chemicals, the use of predominately domestic plant species that may not be representative of plant species in general, the use of predominately agricultural soils which may not be representative of soils in general, and the laboratory test conditions which may not be representative of field conditions. The direction and magnitude of these potential biases is unknown.

The phytotoxicity benchmarks were derived by rank-ordering the LOEC values and then picking a number that approximated the 10th percentile. As with the ER-Ls, statistical fitting was not used because there were seldom sufficient data and because these benchmarks are to be used as screening values and do not require the consistency and precision of regulatory criteria. If there were 10 or fewer values for a chemical, the lowest LOEC was used. If there were more than 10 values, the 10th percentile LOEC value was used. If the 10th percentile fell between LOEC values, a value was chosen by interpolation. Since these benchmarks are intended to be thresholds for significant effects on growth and production, test endpoints that indicate a high frequency of lethality are not appropriate. Therefore, when a benchmark is based on an $LC_{50}$ or on some other endpoint that includes a 50% or greater reduction in survivorship, the value is divided by a factor of 5. This factor is based on the authors' expert judgment. Although there is not a body of data for comparison of lethal and sublethal effects concentrations in tests conducted with the same species and soils, it is the authors' impression that a factor of 5 approximates the ratio $LC_{50}/EC_{20}$.

In all cases, benchmark values were rounded down to one significant figure. This rounding was done for two reasons. First, it is not appropriate to ascribe greater precision to a number than it actually possesses; these benchmarks are very imprecise. Second, the rounding serves to emphasize the fact that the benchmarks are conceptually distinct from the test endpoint values from which they were derived. That is, a LOEC may be a precise estimate of the lowest toxic concentration for a particular plant variety in a particular test system, but when an LOEC is used as a benchmark for all plants in field soils, it is a qualitatively different and much more poorly defined value.

Another source of benchmark values was published reviews of the phytotoxicity literature. When primary literature was unavailable for a particular contaminant, concentrations identified in reviews as thresholds for phytotoxicity were used as benchmarks. In addition, when fewer than three LOEC values were found for a chemical in soil or solution and a toxicity threshold from a review was lower than the lowest LOEC, the toxicity threshold was used as the benchmark for that chemical. Proposed screening benchmarks for phytotoxic effects of contaminants in soils and solutions are presented in Table 1.

This method of deriving screening benchmarks for soil organisms may strike some readers as insufficiently conservative. That impression could result from the fact that the derivation of the benchmark (like the derivation of the ER-L values) implies a significant effect on approximately 10% of the species. However, the authors believe that the method described in this report is sufficiently conservative for the following reasons. First, these benchmarks were derived for a community-level assessment endpoint. Given the water, nutrient, or physical limitations of most soil and litter-dwelling communities, a reduction in growth, reproduction, or functioning of 10% of component species is likely to be acceptable. Second, the benchmarks derived by these methods have proved to be conservative in practice. In some locations for some elements, they are lower than background concentrations (Section 4). This is believed to be caused by the fact that they are based on toxicity tests which dose growth substrates with soluble salts of metals. Therefore, they are much more available than most naturally occurring metals, and even metals at many, if not most, waste sites.

In this report, the authors have attempted to assign levels of confidence to the benchmarks. The criteria that best reflect that confidence are as follows:

1. Low Confidence—Benchmarks based on fewer than 10 literature values.

2. Moderate Confidence—Benchmarks based on 10 to 20 literature values.

3. High Confidence—Benchmarks based on over 20 literature values.

Confidence in a benchmark based on more than 20 reported toxic concentrations may be reduced to moderate if the range of plant species tested is narrow, i.e., no tree species or only one family of plants were tested. Moderate or high confidence benchmarks may be demoted one level if the value approximating the 10th percentile was the lowest concentration tested and caused a greater than 30% reduction in the measured growth parameter. Although these criteria may seem arbitrary, the result is a confidence classification that fairly reflects the authors' professional judgment.

Any scheme for deriving a set of standard ecotoxicological benchmarks is based on assumptions that may be questioned by readers. The procedure used herein is one that is consistent with current regulatory practice and contains a minimum of assumptions or factors. Those who care to make other assumptions or to add safety factors may make use of the data presented herein to calculate their own benchmarks.

**Table 1. Screening benchmark concentrations for the phytotoxicity of chemicals in soil and soil solution**

| Chemical | Soil (mg/kg) | Solution (mg/L) | Chemical | Soil (mg/kg) | Solution (mg/L) |
|---|---|---|---|---|---|
| Aluminum | 50 | 0.3 | 4-Bromoaniline | — | 100 |
| Antimony | 5 | — | 3-Chloroaniline | 20 | — |
| Arsenic | 10 | 0.001 | 4-Chloroaniline | — | 40 |
| Barium | 500 | — | 2-Chlorophenol | — | 60 |
| Beryllium | 10 | 0.5 | 3-Chlorophenol | 7 | — |
| Bismuth | — | 20 | 4-Chlorophenol | — | 50 |
| Boron | 0.5 | 1 | 2-Cresol | — | 50 |
| Bromine | 10 | 10 | 3,4-Dichloroaniline | — | 10 |
| Cadmium | 4 | 0.1 | 2,4-Dichlorophenol | — | 20 |
| Chromium | 1 | 0.05 | 3,4-Dichlorophenol | 20 | — |
| Cobalt | 20 | 0.06 | 2,4-Dinitrophenol | 20 | — |
| Copper | 100 | 0.06 | Di-n-butyl phthalate | 200 | — |
| Fluorine | 200 | 5 | Diethylphthalate | 100 | 20 |
| Iodine | 4 | 0.5 | Furan | 600 | 100 |
| Iron | — | 10 | Heptane | — | 1 |
| Lead | 50 | 0.02 | Hexachlorocyclopentadiene | 10 | 0.1 |
| Lithium | 2 | 3 | Naphthalene | — | 10 |
| Manganese | 500 | 4 | 3-Nitroaniline | — | 70 |
| Methyl mercury | — | 0.0002 | 4-Nitroaniline | — | 40 |
| Mercury | 0.3 | 0.005 | Nitrobenzene | — | 8 |
| Molybdenum | 2 | 0.5 | 4-Nitrophenol | — | 10 |
| Nickel | 30 | 0.5 | Pentachlorophenol | 3 | 0.03 |
| Selenium | 1 | 0.7 | Phenol | 70 | 10 |
| Silver | 2 | 0.1 | PCBs | 40 | — |
| Technetium | 0.2 | 0.2 | Styrene | 300 | 10 |
| Tellurium | — | 2 | 2,3,5,6-Tetrachloroaniline | 20 | — |
| Thallium | 1 | 0.05 | Tetrachloroethene | — | 10 |
| Tin | 50 | 100 | Toluene | 200 | 10 |
| Titanium | — | 0.06 | 4-Toluidine | — | 100 |
| Uranium | 5 | 40 | 2,4,5-Trichloroaniline | 20 | — |
| Vanadium | 2 | 0.2 | Trichloroethane | — | 100 |
| Zinc | 50 | 0.4 | 2,4,5-Trichlorophenol | 4 | — |
| Acenaphthene | 20 | 0.1 | 2,4,6-Trichlorophenol | — | 10 |
| Aniline | — | 200 | Ortho-xylene | — | 1 |
| Biphenyl | 60 | 2 | Xylene | — | 100 |

# 3. TOXICITY DATA REVIEW

Results of the literature review are summarized in Appendixes A and B. A short noncritical review of the literature from which data were derived for the calculation of benchmarks is presented in the following text. All soil experiments were conducted in pots in a greenhouse (glass or screen) unless otherwise noted. Experiments conducted in solution culture were generally conducted in growth chambers although some experimental setups were contained in greenhouses. Confidence in the benchmark for a particular chemical is also discussed in the following text. The criteria used to establish confidence levels are given in Section 2. The units of ppm are equivalent to mg/kg for chemicals in soil and mg/L for chemicals in solution.

Information is also given on the mechanisms of phytotoxicity of the chemicals. The mechanisms of growth reductions measured are seldom discussed in the literature from which toxicity data are extracted for benchmark calculations. This information is offered to allow a better understanding of the potential mechanisms of toxicity of these and related contaminants.

## 3.1 INORGANIC CHEMICALS

### 3.1.1 Aluminum

**Experiments conducted in soil**. Seedling establishment of white clover (*Trifolium repens* L.) in a silt loam soil (pH 5.0) was reduced approximately 30% by the addition of 50 ppm Al as $Al_2(SO_4)_3$ (Mackay et al., 1990), the lowest concentration tested. This lone study does not allow a high degree of confidence in the benchmark.

**Experiments conducted in solution**. Goransson and Eldhuset (1991) evaluated the effect of Al on root and shoot growth of seedlings of Norway spruce (*Picea abies* L.) and Scots pine (*Pinus sylvestris* L.) in a nutrient solution of pH 3.8. The spruce proved much more sensitive to Al with a 33% reduction in root growth weight after 21 days at 8.1 ppm Al in solution (5.4 ppm had no effect). Pine shoot growth rate was reduced 40% with 270 ppm, while 162 ppm Al had no effect.

Godbold and Kettner (1991) measured a 42% reduction in mean root length of 3-wk old Norway Spruce seedlings grown in a nutrient solution (pH 4) containing 5.4 ppm Al ($AlCl_3$) for 8 days. Aluminum at 1.4 ppm had no effect on plant growth.

Nichol and Oliveira (1995) investigated the effect of aluminum in a hydroponic medium on root growth of a barley cultivar (*Hordeum vulgare*). For seeds germinated in the solution containing aluminum at 0.0027 ppm, root growth was inhibited by about 25% two days following germination and by about 60% four days following germination.

Pintro et al. (1996) studied the effect of aluminum (as chloride) in solution on the growth of two cultivars of corn, one aluminum-sensitive and one aluminum-tolerant (*Zea mays* L., HS7777 and C525-M). At 0.27 ppm, aluminum reduced root elongation and root weight of the aluminum-sensitive plants by about 50% and 20%, respectively. The NOEC was 0.13 ppm. A concentration of 0.405 ppm reduced the root elongation of the aluminum-tolerant cultivar by about 30%, with a NOEC of 0.13 ppm. The activities and ionic strengths of aluminum were calculated in the paper.

Zavas et al. (1996) exposed plants from two populations of perennial grass (*Piptatherum miliaceum*) to aluminum (as chloride) in solution for 16 days. The two populations were from a bauxite area and a pasture soil in Greece. Tests were conducted at pH 4.5 and 10. At the lower pH and at an aluminum concentration of 12.9 ppm, the mean root length of plants from the bauxite area was reduced by 73% and that of plants from the pasture soil was reduced by 76%. The NOEC was 2.2 ppm. No toxicity was observed at a pH of 10.

Keltjens (1990) tested the responses of roots and shoots of 1-yr-old Douglas fir (*Pseudotsuga menziesii* L.) seedlings to Al (as chloride) in a pH 3.5 solution at 4, 6, 8, 16, and 32 ppm. Calcium and magnesium were added at 0.1, 0.5, or 2.5 mM. After a 9-month exposure to aluminum at 32 ppm with Ca and Mg present at 0.5 mM, root length was reduced 43%, and root weight was reduced about 30%. Shoot weight was reduced about 40% by exposure to 8 ppm Al with Ca and Mg added at 2.5 mM.

Lin and Myhre (1991) compared the tolerance of citrus rootstock seedlings to growth in solution (pH 4) containing Al (as $Al_2(SO_4)_2$) by measuring root length, shoot height, and plant weight. After 60 days, three of the five rootstocks had reduced weight at 8.3 ppm Al. Percent reduction ranged from 22 to 45% at that concentration. The citrange rootstock root length was decreased 21% at 2.7 ppm Al. The Cleopatra mandarin rootstock had a 30% reduction in weight at 24.4 ppm.

Wheeler and Follet (1991) evaluated the effect of Al as $Al_2(SO_4)_3$ in solution culture (pH 4.7) on root and shoot weights of onions (*Allium cepa* L.), asparagus (*Asparagus officinalis* L.), and squash (*Cucurbita maxima* L.). Root and shoot weights of onions were reduced 68 and 23% after 31 days of growth in solution containing 0.05 ppm (lowest concentration tested). Root and shoot weight of asparagus were reduced 49 and 70% in solution containing 0.13 ppm Al, while 0.05 ppm had no effect. Root weight of squash was reduced 25% after 26 days of growth in solution containing 0.27 ppm while 0.13 ppm had no effect.

McLean and Gilbert (1927) used nutrient solution culture to test the comparative resistance of different plants to Al toxicity. Carrot (*Daucus carota* L.) seedling weight was reduced approximately 75% after 126 days of growth in solution containing 3.6 ppm Al (lowest concentration tested) in two experiments. Radish (*Raphanus sativus* L.) seedling root and shoot weights were reduced 21% after 77 days of growth in solution containing 3.6 ppm Al, while 1.8 ppm had no effect. Turnip (*Brassica rapa* L.) seedling top weight was reduced 39% after 77 days of growth in solution containing 7.2 ppm Al, while 3.6 ppm had no effect. In two experiments with slightly different nutrient solutions, beet seedling weight was reduced approximately 25% after 126 days of growth in solution containing 1.8 ppm Al (lowest concentration tested). Seedling weight was diminished 74% by 1.8 ppm Al (lowest concentration tested) in a third experiment. In two 56-day experiments in slightly different nutrient solutions, lettuce weight was reduced 39% by 1.8 ppm (0.9 ppm had no effect) and 55% by 2.7 ppm Al (1.8 ppm had no effect) in solution.

In a third experiment lasting 42 days, lettuce top weight was reduced 25% by 1.1 ppm, while 0.5 ppm Al had no effect. Cabbage and oat seedling weights were reduced 43% and approximately 25% by 7.2 ppm Al (lowest concentration tested) after 98 and 63 days, respectively. After 77 days, barley seedling root and shoot weights were reduced 47 and 22% by 1.8 ppm Al (lowest concentration tested). After 63 days, rye seedling root weight was reduced 22% by 1.8 ppm Al (lowest concentration tested). In a second experiment, plants grown in an alternate nutrient solution suffered a root weight of 25% in the presence of 3.6 ppm Al, while 1.8 ppm had no effect.

Wallace and Romney (1977a) grew rice (*Oryza sativa* L.) and soybean (*Glycine max* L.) seedlings in solution culture containing Al as $Al_2(SO_4)_3$ for 13 days. Root and shoot weights of rice were reduced 28 and 27% by 2.7 ppm Al, while 0.27 ppm had no effect. Leaf weight of soybeans was reduced 33% by the same concentration.

MacLeod and Jackson (1967) tested two varieties of barley (*Hordeum vulgare* L.) for tolerance to 4, 6, 8, 10, or 12 ppm Al (as $AlCl_3$) in a pH 4.3 nutrient solution. After 30 days of growth, root and shoot weights of one variety were reduced approximately 50% by 10 ppm Al, while those of the other variety were reduced approximately 30% by 6 ppm Al.

Wong and Bradshaw (1982) evaluated the effect of Al on root and shoot length of ryegrass (*Lolium perenne* L.) grown in solution (pH 7) with Al added as $KAl(SO_4)_2$. After 14 days, they found a 29% reduction in the length of the longest root in response to 0.63 ppm (lowest concentration tested).

Sasaki et al. (1994) evaluated the effect of Al as $AlCl_3$ in solution culture (pH 4.5) on root elongation of wheat cultivars (Triticum sativum L.). Root elongation was reduced 50% after 5 days growth in solution containing 0.27 ppm, while 0.14 ppm had no effect.

Llugany et al. (1995) evaluated the effect of Al as $AlCl_3$ in nutrient solution culture (pH 4.3) on root elongation of 4-d old seedlings of maize cultivars (Zeya mays L.). For three of the four cultivars, root elongation was reduced 23 to 37% after 1 day of growth in the solution containing 0.54 ppm, the lowest concentration tested. Root elongation in the fourth cultivar during the same time period was reduced 36% in the presence of 1.35 ppm Al, while 0.54 ppm had no effect.

The authors have high confidence in the benchmark of 0.3 ppm Al. The low LOEC values are based on experiments with seedlings of field and horticultural crops. Trees, especially pines, appear to have the greatest tolerance to Al.

**Mechanism of phytotoxicity**. Aluminum interferes with cell division in roots; decreases root respiration; fixes P in unavailable forms in roots; interferes with uptake, transport, and use of Ca, Mg, P, K, and water; and interferes with enzyme activities (Foy et al. 1978). Symptoms of toxicity include stubby, brittle roots; stunting; late maturity; and collapse of growing points. Seedlings are more susceptible to damage from Al toxicity than are older plants.

### 3.1.2 Antimony

**Experiments conducted in soil**. No primary reference data exist that describe toxicity of Sb to plants grown in soil. The benchmark is based on a report of unspecified toxic effects on plants grown in a surface soil with the addition of 5 ppm Sb (Kabata-Pendias and Pendias 1984)). The authors have low confidence in the benchmark based on this study alone.

**Experiments conducted in solution**. No reference data exist that show toxicity of Sb to plants grown in solution.

**Mechanism of phytotoxicity**. Antimony is considered a nonessential metal and is easily taken up by plants if available in the soil in soluble forms (Kabata-Pendias and Pendias 1984). The only information found on phytotoxicity was a secondary reference noting undefined, qualitative phytotoxic effects on plants grown in a surface soil (Kabata-Pendias and Pendias 1984).

### 3.1.3 Arsenic

**Experiments conducted in soil**. The tolerance of spruce seedlings to As in soil was tested in field plots by Rosehart and Lee (1973). Three-year-old seedlings grown 335 days in soil to which 1000 ppm As was added as As(III) (lowest concentration tested) experienced a 50% reduction in height.

Deuel and Swoboda (1972) assessed the toxicity of As(III) added to two soils on the shoot weight of cotton (*Gossypium hirsutum* L.) and soybeans grown from seed for 6 weeks. In the fine sandy loam soil, shoot weight of both crops were reduced (cotton 22%; soybeans 45%) in the presence of 11 ppm As, the lowest concentration tested. Soybean growth in a black clay soil was reduced 28% by the addition of 22.4 ppm As, the lowest concentration tested. Cotton growth in this soil was reduced 29% by the addition of 89.6 ppm As.

Woolson et al. (1971) tested the toxicity of three sources of As(V) on corn grown from seed for 4 weeks in a loamy sand (pH 7.1). Corn fresh weight reductions rose from less than 10% with the addition of 10 ppm As in any form, to almost 100% for $NaH_2AsO_4$, over 75% for Al $(H_2AsO_4)_3$, and about 65% for $Ca(H_2AsO_4)_2$ with the addition of 100 ppm As.

Jiang and Singh (1994) assessed the toxicity of As (III) and As (V) added to the two soils on the yield of barley and ryegrass grown from seed for 1 year in a greenhouse. The soils tested were a loam (pH 4.9, 3% organic carbon, and 19% clay) and a sand (pH 5.6, 0.4% organic carbon, and 3% clay). Sodium arsenite was more toxic to barley plants than sodium arsenate in both soils, with the greatest toxicity occurring in the sand (24% decrease at 2 ppm, the lowest concentration tested). Arsenic (V) at 250 ppm was associated with greater reduction in yield of ryegrass (63%) than the same concentration of As (III) in the loam soil (22%). In the sand, sodium arsenite reduced yield of ryegrass 34% at 50 ppm. A concentration of 250 ppm As (V) caused a 91% decrease in yield while 50 ppm had no effect. Confidence in a soil benchmark value of 10 ppm is moderate.

**Experiments conducted in solution**. Mhatre and Chaphekar (1982) tested several species at germination stage for their response to As. Seeds of sorghum, alfalfa (*Medicago sativa* L.), mung bean (*Phaseolus aureus* L.), cluster bean (*Cyamopsis tetragonoloba* L.), and radish were allowed to germinate in solutions containing 0.001, 0.01, 0.1 or 1 ppm As as $As_2O_3$ (As III). Germination counts after 24 hours showed no effect of As. After 5 days, root length of cluster bean was reduced 29% by 0.001 ppm As. Root length of radish was reduced 21% by the addition of 0.01 ppm. Root and shoot lengths of alfalfa and mung bean were reduced (55 and 40%, 87 and 57%) by the addition of 1 ppm As.

The concentrations of As (V), from $Na_2HAsO_4$, required for a 50% reduction in seed germination and root length of mustard (*Sinapis alba*) after 3 days of exposure in solution (pH 7.3), was reported by Fargasova (1994). $LC_{50}$ for germination was 30 ppm and $EC_{50}$ for root length was 5.5 ppm As.

Bowen (1979) reported unspecified reductions in plant growth in a solution containing 0.02 ppm As.

Confidence in the solution benchmark of 0.001 ppm is low because there are less than 10 values and a limited variety of plant species tested.

**Mechanism of phytotoxicity**. Arsenic is not essential for plant growth. It is taken up actively by roots, with arsenate being more easily absorbed than arsenite. Arsenic and phosphate ions are likely taken up by the same carrier (Asher and Reay 1979). The phytotoxicity is strongly affected by the form in which it occurs in soils. Arsenite is more toxic than arsenate, and both are considerably more toxic than organic forms (Peterson et al. 1981). In experiments with toxic levels of As, rice and legumes appear to be more sensitive than other plants. Symptoms include wilting of new-cycle leaves, followed by retardation of root and top growth, and leaf necrosis (Aller et al. 1990). Because As is chemically similar to P, it is translocated in the plant in a similar manner and is able to replace P in many cell reactions. Arsenic (III) probably reacts with sulphydryl enzymes leading to membrane degradation and cell death. Arsenic (V) is known to uncouple phosphorylation and affect enzyme systems (Peterson et al. 1981). The mechanism of toxicity of organo-arsenicals is unclear.

### 3.1.4 Barium

**Experiments conducted in soil.** Chaudhry et al. (1977) investigated the effects of Ba added as $Ba(NO_3)_2$ on shoot weight of barley and bush beans (*Phaseolus vulgaris* L.) grown from seed for 14 days in a loam soil. Shoot growth of barley was reduced 38% after 14 days by the addition of 500 ppm Ba, the lowest concentration tested. Shoot growth of bush beans was reduced 30% after 14 days by the addition of 2000 ppm Ba, but was not reduced at the next lowest level, 1000 ppm.

Confidence in a benchmark value of 500 ppm is low due to lack of supporting data.

**Experiments conducted in solution.** There were no reference data describing toxicity of Ba to plants grown in solution.

**Mechanism of phytotoxicity.** Barium is commonly present in plants but is not an essential component of plant tissues. It is taken up easily from acid soils (Kabata-Pendias and Pendias 1984). Mechanisms of toxicity may include competition with Ca for root uptake (Wallace and Romney 1971).

### 3.1.5 Beryllium

**Experiments conducted in soil.** Few tests of the toxicity of Be to plants grown in soil have been conducted. Confidence in the benchmark is low because the lowest of the three values is from a report of unspecified toxic effects on plants grown in a surface soil with the addition of 10 ppm Be (Kabata-Pendias and Pendias 1984).

**Experiments conducted in solution.** Romney et al. (1962) reported a 33% reduction in the weight of bush beans when grown for 48 days in a pH 5.3 nutrient solution containing 0.5 ppm Be (lowest concentration tested).

Sajwan et al. (1997) investigated the effect of beryllium on the mass of above-ground soybean plants in a sand and loamy sand soil. The addition of 25 ppm of beryllium to soil, the lowest concentration tested, led to a 49% reduction in soybean biomass in the sand and a 46% reduction in biomass in the loamy sand after 14 days. Additional tests undertaken with limed soil also showed toxicity at the 25 ppm concentration.

Romney and Childress (1965) investigated the effect of 2, 4, 8, and 16 ppm Be (as $BeCl_2$; pH 5.3) on growth of barley, alfalfa, pea (*Pisum sativum* L.), and lettuce (*Latuca sativa* L.). Barley (20 days), pea (24 days), and lettuce (28 days) weights were reduced 50, 21, and 37%, respectively, by 2 ppm Be. After 54 days, alfalfa weight was reduced 25% by 4 ppm Be.

The effects of Be, from $BeSO_4$, on germination and radicle length after 3 days of growth in solution of radish, cabbage (*Brassica oleracea* L.), turnip, lettuce, wheat, and millet (*Panicum miliaceum*) were determined by Carlson et al. (1991). There was no effect on seed germination up to 40 ppm Be. Treatment levels were 0, 0.5, 1, 2.5, 5, 7.5, 10, 20, 30, and 40 ppm Be. A concentration of 0.5 ppm reduced radicle length of lettuce and turnip by 62 and 63%. A concentration of 2.5 ppm reduced radicle length of cabbage by 35%. Five ppm Be reduced radicle length of radish by 32%, 20 ppm caused a 30% decrease in wheat, and 40 ppm reduced radicle length of millet by 35%.

Confidence in the benchmark for Be in solution (0.5 ppm) is low. There were 11 values to consider but a greater than 30% reduction occurred in the measure approximating the 10th percentile.

**Mechanism of phytotoxicity**. Soluble forms of Be are easily taken up by plants, probably in a manner similar to Ca and Mg, but it is not readily translocated from roots to shoots (Peterson and Girling 1981). Be has been reported to inhibit seed germination, enzyme activation, and uptake of Ca and Mg by roots. Common symptoms are brown, retarded roots and stunted foliage (Romney and Childress 1965).

### 3.1.6 Bismuth

**Experiments conducted in soil.** No reference data were available that describe toxicity of Bi to plants grown in soil.

**Experiments conducted in solution.** There were no primary reference data showing toxicity of Bi to plants grown in solution. The benchmark is based on a report of unspecified toxic effects on plants grown in a solution with the addition of 27 ppm Bi (Bowen, 1979). The authors have low confidence in the benchmark of 20 ppm Bi based on this work alone.

**Mechanism of phytotoxicity**. Although Bi has been shown to reduce the weight of some plants in solution culture (Bowen, 1979), no information on specific mechanisms of toxicity was found.

### 3.1.7 Boron

**Experiments conducted in soil.** John et al. (1977) investigated the effects of B added as $H_3BO_3$ on shoot weight of corn seedlings grown 7 weeks in muck and two silt loam soils (growth chamber). Addition of 50 ppm B to the muck soil (pH 4.5; % organic matter 56; CEC 117 meq/100g soil) resulted in a 56% reduction in plant growth, while the next lowest concentration tested, 10 ppm B, did not cause a 20% decrease. Growth was reduced 37% by the addition of the lowest concentration tested (0.5 ppm) in the Marble Hill silt loam soil (pH 5.7; % organic matter 6; CEC 23 meq/100g soil). Growth was reduced 83% by the addition of 50 ppm B in the Monroe silt loam soil (pH 5.7; % organic matter 3; CEC 16 meq/100g soil), but not reduced by 10 ppm added B .

Confidence in a benchmark value of 0.5 ppm is low because it is based on fewer than 10 values.

**Experiments conducted in solution**. Wallace et al. (1977b) evaluated the effect of B (as $H_3BO_3$) on leaf, stem, and root weights of bush bean seedlings in solution. After 16 days, root and leaf weights were reduced 35 and 45% by 5.4 ppm B, while 1.1 ppm had no effect.

Bowen (1979) reported unspecified toxic effects on plants grown in a solution with the addition of 1 ppm B.

Confidence in the benchmark of 1 ppm for B is low because it is based on only two values.

**Mechanism of phytotoxicity**. Boron is a plant micronutrient involved in transport of sugars across membranes, synthesis of nucleic acids, and protein utilization. It is rapidly taken up, mainly as the neutral $B(OH)_3$ molecule and equally distributed between roots and shoots (Wallace and Romney 1977b).

Toxicity symptoms include needle tip necrosis and discoloration in pines (Neary et al. 1975) and burning of leaf edges in other plants. Grasses and legumes appear to have greater than average tolerance to high B concentrations (Gupta 1984), and pines appear to be particularly sensitive (Stone and Baird, 1956).

### 3.1.8 Bromine

**Experiments conducted in soil.** There were no primary reference data showing toxicity of Br to plants grown in soil. Kabata-Pendias and Pendias (1984) reports unspecified toxic effects on plants grown in a surface soil with the addition of 10 ppm Br. Confidence in this benchmark is low. Newton and Toth (1952) found no toxicity symptoms or reduction in weight of tomato (*Lycosperisicon esculentum* L.) at concentrations up to 20 ppm Br in soil.

**Experiments conducted in solution.** There were no primary reference data describing toxicity of Br to plants grown in solution. The benchmark is based on a report of unspecified toxic effects on plants grown with the addition of 15 ppm Br (Martin 1966a). Confidence in the benchmark of 10 ppm based on this work is low.

**Mechanism of phytotoxicity.** Bromine can substitute for part of the $Cl^-$ requirement of plants. Symptoms of excess Br are similar to those of excess salt (leaf edge necrosis and poor seed germination) (Martin et al. 1956).

### 3.1.9 Cadmium

**Experiments conducted in soil.** Miles and Parker (1979a) investigated the effects of Cd added as $CdCl_2$ on seed germination and root and shoot weights of a variety of native plants grown from seed for 6 weeks in a sandy soil (pH 4.8, % organic matter 1.9, CEC 6.3 meq/100g soil). Seed germination of Black-eyed Susan (*Rudbeckia hirta*), and root and/or shoot growth of Black-eyed Susan, rough blazing star (*Listris spicata*), long-fruited thimbleweed (*Anemone cylindrica*), and wild bergamot (*Monarda fistulosa*) were reduced by more than 20% with the addition of 10 ppm Cd, the lowest concentration tested. Growth of Kentucky bluegrass (*Poa pretensis*) roots and shoots, little bluestem (*Andropogon scoparius*) roots, and poison-ivy (*Rhus radicans*) roots and shoots was reduced by approximately 90%, 60%, and 70%, respectively, with the addition of 30 ppm Cd where 10 ppm Cd did not have an effect.

Miles and Parker (1979b) found approximately 45% reductions in root and shoot weights of little bluestem grown from seed for 12 weeks in a sandy soil (pH 7.8, % organic matter 2.5, CEC 12 meq/100g soil), when 10 ppm Cd as $CdCl_2$ was added. This was the only concentration tested.

In a pot culture starting with 2-year-old beech (*Fagus sylvatica* L.), trees growing in an organic-rich forest soil (pH 4.8), Hagemeyer et al. (1993) measured an approximately 25% reduction in annual ring growth in the presence of 5.6 ppm 1M ammonium acetate-extractable Cd when trees were grown for two seasons. Cadmium at 1.1 ppm did not affect growth. The results of this study are not directly comparable to others that report the amount of Cd added to the soil; however, the information is presented for reference to increase the number of plant types covered.

Dixon (1988) measured the response of red oak (*Quercus rubra* L.) seedlings grown for 16 weeks in a sandy loam soil (pH 6, % organic matter 1.5) with addition of Cd ($CdCl_2$). Cadmium at 20 ppm reduced tree weight by 28%, while 10 ppm had no effect.

Carlson and Bazzaz (1977) measured root, woody stem, green stem and foliage weights, and main stem diameter of 2 to 3-year old American sycamore (*Plantanus occidentalis* L.) saplings associated with 90 days of exposure to Cd as $CdCl_2$ added to a silty clay loam soil. The lowest concentration tested (5 ppm Cd) was responsible for a 30% reduction in leaf weight.

Burton et al. (1984) grew Sitka-spruce (*Picea sitchensis*) seedlings from 4 weeks of age in a mixture of acidic peaty gley soil and sand with Cd added (0.1, 0.4, 1, 2, 4, 8, and 16 ppm as $CdCl_2$). Two ppm Cd lead to a reduction of about 45% in root and shoot weight of the 18-week old seedlings.

John et al. (1972b) reported the effects of Cd on radish growth (from seed for 3 weeks in a growth chamber) averaged more than 30 surface soils with the following characteristics: pH of 5.6 (±0.8), % organic matter 12.9 (±15.7), % clay 19.3 ± 14.4, CEC 32.8 meq/100g soil (± 25.2). Root weight was reduced by an average of 67%, and shoot weight by an average of 47%, by the addition of 100 ppm Cd as $CdCl_2$, the lowest concentration evaluated.

Reber (1989) found a 21% reduction in wheat growth from seed for 4 weeks in a Phaeosem soil (pH 6.9, % organic matter 2.2) with the addition of 113 ppm Cd as Cd acetate ($C_4H_6CdO_4$). Only 14 ppm Cd were required to get this same reduction in an acid cambisol soil (pH 5.6, % organic matter 1.7).

In a mixture (1:1) of sandy and clay loam soils (pH 8.4, % organic matter 0.5, CEC 15 meq/100g soil), Singh et al. (1991) measured a 44% reduction in the grain and straw yield of wheat grown from seed to maturity with the addition of 20 ppm Cd as $CdCl_2$.

Carlson and Rolfe (1979) found that 100 ppm Cd added as $CdCl_2$ to a soil was necessary to give a 33% reduction in clipping weight of ryegrass grown in a silt loam soil (pH 5.9, CEC 21 meq/100g soil) from seed.

Number of soybean seeds produced per plant was decreased by 67% when plants were grown in an average garden soil to which 10 ppm Cd was added as $CdCl_2$ (Aery and Sakar 1991). Cadmium at 5 ppm had no effect. Plants were grown from seed to maturity.

Strickland et al. (1979) evaluated the effects of Cd (1.25, 2.5, 5, 10, and 20 ppm Cd as $CdCl_2$) on soybeans grown from seed for 6 weeks in varying ratios of sand and peat. While increasing the amount of organic matter in the mixture from 0 to 2%, the concentration of Cd required to reduce plant growth by 20% was increased from 1.25 ppm (lowest concentration tested) to 20 ppm.

Hassett et al. (1976) measured a 43% reduction in corn root length after 7 days of growth from seed in a loamy sand soil (pH 6.5, % organic matter 2, CEC 2 meq/100g soil) to which 25 ppm Cd (as $CdCl_2$) was added. Cadmium at 15 ppm did not affect growth.

Traynor and Knezek (1973) measured a 24% reduction in corn plant weight with the addition of 28 ppm Cd (as $CdCl_2$; lowest concentration tested) to a sandy soil (pH 5, % organic matter 2, CEC 6 meq/100g soil) in which the plants had been grown for 5 weeks from seed.

Muramoto et al. (1990) measured the effects on wheat and rice grown from seed to maturity of addition of Cd as CdO to an alluvial soil (pH 6). Root and shoot weights of rice were reduced 32 and 21% by 100 ppm Cd, while 30 ppm had no effect. Wheat grain yield was reduced 34% by 30 ppm Cd, while 10 ppm had no effect.

Sadana and Singh (1987a and b) investigated the effects of Cd added to a loamy sand soil (pH 8.4, % organic matter 1) on lettuce and grain yield of wheat grown from seed to maturity. Lettuce growth was reduced 23% by the addition of 4 ppm Cd and wheat grain yield was reduced by 28% by 10 ppm Cd (lowest concentration tested).

Miller et al. (1976) investigated the effects of 1, 10, and 100 ppm Cd (as $CdCl_2$) on vegetative growth of soybeans from seed for 28 days in soils with a range of pH and CEC values. There was an average of 50% (range 33-77%) reduction in shoot weight of crops grown in three silt loam and one loamy sand soil after the addition of 10 ppm Cd. These soils had pH values ranging from 4.5 to 7.0, and CEC values from 2 to 9 meq/100g soil. Soybeans in one silt loam soil (pH 5.5, CEC 8 meq/100g soil) experienced a 30% reduction in shoot weight after addition of 1 ppm Cd. In another silt loam (pH 6.5, CEC 16 meq/100g soil), a 47% reduction in shoot weight was seen when 100 ppm Cd was added. Corn (*Zea mays* L.) grown from seed for 31 days in a loamy sand used in the 1976 work (pH 6, CEC 2 meq/100g soil) experienced a 28% decrease in plant weight after addition of 2.5 ppm Cd (lowest concentration tested) (Miller et al. 1977).

Bingham et al. (1975) evaluated the effects of a range of Cd concentrations added as $CdSO_4$ on a variety of horticultural crops grown from seed to maturity in a silt loam soil (pH 7.5, CEC 14 meq/100g soil). Additions of Cd (in ppm) causing a 25% reduction in shoot or reproductive portion weights were as follows: spinach (*Spinacia oleracea* L.) 4, radishes 96, lettuce 13, carrots 20, soybean 5, curlycress (*Lepidium sativum* L.) 8, corn 18, turnip 28, field bean (*Phaseolus vulgaris* L.) 40, wheat 50, tomato and zucchini (*Curcurbita pepo* L.) 160, and cabbage 170.

John (1973) evaluated the effects of 40 and 200 ppm Cd added as $CdCl_2$ on a variety of horticultural crops grown to maturity in a silt loam soil (pH 5.1, % organic matter 12, CEC 38 meq/100g soil). Addition of 40 ppm Cd caused a reduction in plant weights of spinach, peas, and radishes, and grain yield of oats (*Avena sativa* L.) by 96%, 32%, 27%, and 37%, respectively. Addition of 200 ppm Cd caused a reduction in plant weights of lettuce, broccoli (*Brassica oloeracea* L.), cauliflower (*Brassica oleracea* L.), and carrots by 90%, 63%, 97%, and 95%, respectively.

Haghiri (1973) determined the effects of additions of 2, 5, 10, and up to 100 ppm Cd as $CdCl_2$ to a silty clay loam soil (pH 6.7, % organic matter 4, CEC 31 meq/100g soil) on dry matter yield of several crops. Growth of lettuce and radish were reduced 40 and 36% by the lowest treatment level after 37 days and 26 days, respectively. Weights of wheat were reduced by 29% by 5 ppm Cd, and those of soybeans about 50% by addition of 10 ppm Cd. Both crops were grown from seed for 5 weeks.

In two studies using Brown earth soils, Khan and Frankland investigated the effects of Cd added as $CdCl_2$, the less soluble CdO, or a combination, on growth of radish (1983, 1984), wheat and oats (1984). Radish root and shoot growth were reduced 22% by the addition of 10 ppm Cd as $CdCl_2$, or 100 ppm as CdO (29%), to a soil having a pH of 5.4 (1983). Addition of 50 ppm as $CdCl_2$+CdO (1:1) reduced radish root growth 43% in soil having a pH of 4.6 (1984). The plants were grown from seed for 42 days. Wheat growth was reduced 61% by the addition of 50 ppm Cd as $CdCl_2$ and 47% by the addition of 100 ppm CdO. Oat growth was reduced 25% by the addition of 10 ppm Cd as $CdCl_2$. All concentrations were the lowest tested. Wheat and oats were grown from seedlings for 42 days.

Adema and Henzen (1989) calculated $EC_{50}$ concentrations for effects of Cd added as $CdCl_2$ on lettuce, tomato, and oats grown in a growth chamber from seed for 14 days. The $EC_{50}$ for lettuce in a humic sand soil (pH 5.1, % organic matter 3.7) was 136 ppm, while in a loam soil (pH 7.4, % organic matter 1.4) it was 33 ppm Cd. The $EC_{50}$ for tomato in the humic sand soil was 16 ppm, while in the loam soil it was 171 ppm Cd. The $EC_{50}$ for oats in the humic sand soil was 97 ppm, while in the loam soil it was 159 ppm Cd.

Two cultivars of cotton were tested for tolerance to Cd in soil (Rehab and Wallace, 1978). Two-week-old seedlings grown for 35 days in soil (pH 6.8) to which 300 ppm Cd was added (lowest concentration tested) experienced reduced leaf and stem weights—75 and 83% for the first cultivar and 40 and 78% for the second.

Confidence in a benchmark value of 4 ppm Cd is high because of the high number (74) of values available for its derivation. Approximately 40% of the concentrations responsible for greater than 20% reductions in plant growth parameters fall between 1 and 10 ppm Cd added to soil. This range includes wild and cultivated plants such as legumes, trees, grasses, leafy vegetables and other dicotyledonous plants in soils with a relatively wide range of physical and chemical characteristics.

**Experiments conducted in solution.** The effect of Cd, as $CdSO_4$, on root elongation of 3-week-old Norway spruce seedlings grown for 7 days in nutrient solution (pH 4) was examined by Lamersdorf et al. (1991). The only concentration tested, 0.11 ppm Cd, reduced root elongation by 23%.

Al-attar et al. (1988) investigated the effect of cadmium acetate on the length and weight of the roots and shoots of perennial ryegrass (*Lolium perenne*) seedlings in solution. A concentration of 0.001 ppm, the lowest concentration tested, resulted in a 20% reduction in root dry weight, a 10% decrease shoot dry weight, and no decrease in shoot or root length.

Kummerova and Brandejsova (1994) studied the toxicity of cadmium (as nitrate) to young maize plants in solution. A concentration of 1.12 ppm, the lowest concentration tested, was associated with a 40% decrease in stalk weight.

Ouzounidou et al. (1997) studied the effect of cadmium (as $Cd(NO_3)_2$) in nutrient solution on root and shoot-leaf length of wheat (*Triticum aestivum*). The lowest concentration tested, 29.8 ppm, resulted in a 53% decrease in root length,a 40% decrease in shoot-leaf length, a 42% reduction in root mass, and a 17% decrease in shoot mass compared to control plants.

Greger et al. (1991) exposed sugar beet (*Beta vulgaris*) seedlings to a series of concentrations of cadmium in a nutrient solution. A reduction of 46% dry shoot weight and 42% dry plant weight occurred at 2.25 ppm. The NOEC was 0.56 ppm. Root weight and growth rate were reduced by less than 20%.

Gussarsson (1994) investigated the effect of cadmium chloride on the growth rate of birch (*Betula pendula*) seedlings in a nutrient solution. The percentage dry weight increase after eight days of cadmium exposure was 20% to 25% lower for shoots exposed to 0.056 ppm than for control shoots. The NOEC was 0.022 ppm. No toxic effect on root growth was observed at concentrations up to 2 ppm, the highest concentration tested.

Godbold and Huttermann (1985) measured a 30% reduction in root elongation rate of 4-wk old Norway spruce seedlings grown in a nutrient solution (pH 4.3) containing 0.56 ppm Cd ($CdSO_4$; lowest concentration tested) for 7 d.

Misra et al. (1994) evaluated the effects of several metals on seed germination and root growth of broad bean (Vicia faba). Seed germination was not affected by Cd ($CdCl_2$) at concentrations up to 10 ppm Cd in nutrient solution. Root elongation of plants exposed for 3 days to 6 ppm Cd was reduced 25%, while 4 ppm had no effect.

Wallace (1979) found 98 and 94% decreases in root and shoot weights of bush bean when grown for 15 days in nutrient solution (pH 5) with 11 ppm Cd (as $CdSO_4$), while 0.11 ppm had no effect on growth.

Stiborova et al. (1986) measured a 31% decrease in seedling weight of corn when germinated and grown for 10 days in nutrient solution with 0.11 ppm Cd (as $CdSO_4$; lowest concentration tested).

The effect of Cd on weight and grain yield of 2-week-old corn seedlings grown in nutrient solutions containing $CdCl_2$ was examined in three experiments by Iwai et al. (1975). Seedlings grown for 58 days in pH 5.5 solution experienced 21 and 32% reductions weight and grain yield with 0.1 ppm Cd, while 0.01 ppm had no effect. In an experiment conducted with the same solution but lasting only 19 days, 1 ppm Cd was required to reduce plant weight 23%, while 0.1 ppm had no effect. In a third experiment looking at the effect of pH and toxicity of Cd by using nutrient solutions of pH 4, 5, and 6, plants were grown for 12 days. Plant weight was reduced in all pH treatments by 2 ppm Cd (37, 41, and 45% reductions, respectively) while 0.2 ppm had no effect.

El-Enany (1995) measured 25, 32, and 39% decreases in seed germination, radicle length, and fresh plant weight of corn when germinated and grown for 5 d in nutrient solution with 45 ppm Cd (as $CdCl_2$; lowest concentration tested).

Rascio et al. (1993) found reductions of approximately 45 and 35% in root and shoot length of corn seedlings grown 18 days in nutrient solution containing 28.1 ppm Cd (as $Cd(NO_3)_2$. Cadmium concentration of 11.2 ppm had no effect.

Wong and Bradshaw (1982) measured 37 and 27% decreases in lengths of longest root and shoot of ryegrass when germinated and grown for 14 days in nutrient solution (pH 7) with 1.25 ppm Cd (as $CdSO_4$; lowest concentration tested).

Patel et al. (1976) found 55 and 24% decreases in root and stem weights of chrysanthemum seedlings when grown for 21 days in nutrient solution with 0.11 ppm Cd (as $CdSO_4$; lowest concentration tested).

Cunningham et al. (1975) examined the effect of Cd on leaf, stem, and root weight of 4-day-old soybean seedlings grown for 21 days in nutrient solution (pH 5.2). A concentration of 0.05 ppm (the lowest concentration tested) reduced leaf, stem and root weights by 73, 62, and 38%, respectively.

In 1977, Cunningham reported 56, 47, and 53% reductions in leaf, stem, and root weights of soybean seedlings when grown for 21 days in nutrient solution (pH 6.2) with 0.05 ppm Cd (as $Cd(NO_3)_2$; lowest concentration tested).

Adema and Henzen (1989) evaluated the effect of Cd (as $CdCl_2$) on germination and growth of lettuce, tomato, and oat seedlings in nutrient solution. They report 50% reductions in top growth weight at 0.84 ppm for lettuce, 3 ppm for tomato, and 6 ppm for oats.

Turner (1973) grew seedlings of various vegetables in nutrient solution (pH 6.3) containing Cd at 0.01, 0.1, and 1 ppm Cd as $CdCl_2$. Carrots were the least tolerant with a 25% reduction in top weight at 0.01 ppm Cd after 35 days. Tomato seedlings grown for 14 days showed a 45% reduction in top weight with 0.1 ppm. Beets (*Beta vulgaris* L.) and Swiss chard (*Beta vulgaris* L.), both grown for 35 days, had reductions of 54% in top weight at 1 ppm Cd.

Inouhe et al. (1994) grew 7-d old seedlings of various crops in solution containing Cd as $CdSO_4$. Sesame (*Sesamum indicum*), pea, radish, cucumber, tomato, and Azuki bean (*Vigna angularis*) experienced reduced root growth (40 to 85%) at 1 ppm Cd, the lowest concentration tested. Lettuce and barley were more tolerant with 63 and 35% reductions at 3.4 ppm Cd after 7 d. Root growth of oat seedlings was reduced 50% when grown in solution containing 6.8 ppm Cd.

Jalil et al. (1994) measured a 24% reduction in shoot dry weight of 2-d old wheat seedlings when grown for 13 d in nutrient solution (pH 5.5) with 0.1 ppm Cd (as $CdCl_2$; lowest concentration tested).

Wang (1994) evaluated the effects of several metals and organic compounds on radicle weight of rice seed germinated and grown for 6 d in solution. The calculated $EC_{50}$ for Cd ($CdCl_2$) was 1.4 ppm.

Page et al. (1972) grew corn, field bean, beet, and turnip seedlings for 21 days in nutrient solution containing Cd as $CdSO_4$ at 0.1, 0.25, 0.5, and 1 ppm. Weights of bean, beet, and turnip were reduced 36, 45, and 22% by 0.1 ppm Cd. Weight of corn was reduced 33% by 0.5 ppm. They also grew lettuce, tomato, pepper, cabbage, and barley for 21 days in solutions containing 1, 2.5, and 5 ppm Cd. Weights of lettuce, tomato, pepper, and barley were reduced 53, 25, 38, and 30% by 1 ppm. Cabbage had a 24% reduction in weight with 2.5 ppm Cd.

Garate et al. (1993) evaluated the effect of Cd (as $CdSO_4$) in nutrient solution on root and leaf growth of lettuce and endive (*Lactuca serriola* L.). They found a 28% reduction in root weight of giant endive after 35 days of growth with 0.1 ppm Cd (lowest concentration tested).

The concentrations of Cd, from $CdCl_2$, required for a 50% reduction in seed germination and root length of mustard after a 3-day exposure in solution (pH 6.6) was reported by Fargasova (1994). LC50 for germination was 692 ppm and $EC_{50}$ for root length was 48 ppm Cd.

The effect of Cd, as $CdCl_2$, on plant weight of cotton grown in nutrient solution (pH 5.5) was evaluated by Rehab and Wallace (1978). Plant weight was reduced 47% by 1.1 ppm Cd, the lowest concentration tested.

Confidence in the 0.1 ppm benchmark is high. It is based on 52 values from experiments using a variety of plant species.

**Mechanism of phytotoxicity**. Cadmium is not essential for plant growth. If present in available form, it is readily taken up by the roots and translocated through the plant and accumulated. Cadmium is chemically similar to Zn, an essential element. Competition between the two for organic ligands may explain some of the toxic effects of Cd and the ameliorative effects of Zn on Cd toxicity. Cadmium depresses uptake of Fe, Mn, and probably Ca, Mg, and N (Wallace et al., 1977e; Iwai, et al. 1975). Cadmium is toxic at low concentrations. Symptoms resemble Fe chlorosis and include necrosis, wilting, reduced Zn levels, and reduction in growth. The mechanisms of toxicity include reduced photosynthetic rate, poor root system development, reduced conductivity of stems, and ion interactions in the plant. Agronomic crops are more sensitive to Cd toxicity than trees (Adriano 1986).

### 3.1.10 Chromium

**Experiments conducted in soil**. Turner and Rust (1971) investigated the effect of Cr added as Cr(VI) on soybean seedlings grown 3 days in a loam soil. Fresh shoot weight was reduced 30% by 30 ppm Cr, while 10 ppm had no effect.

Adema and Henzen (1989) calculated $EC_{50}$ concentrations for effects of Cr added as Cr(VI) on lettuce, tomato and oats grown in a growth chamber from seed for 14 days. The $EC_{50}$ for lettuce in a humic sand soil (pH 5.1, % organic matter 3.7) was greater than 11 ppm, while in a loam soil (pH 7.4, % organic matter 1.4) it was 1.8 ppm Cr. The $EC_{50}$ for tomato in the humic sand soil was 21 ppm, while in the loam soil it was 6.8 ppm Cr. The $EC_{50}$ for oats in the humic sand soil was 31 ppm, while in the loam soil it was 7.4 ppm Cr.

Confidence in the benchmark of 1 ppm Cr is low because of the small number of studies on which it is based.

**Experiments conducted in solution.** Adema and Henzen (1989) calculated $EC_{50}$ concentrations for effects of Cr added as $K_2Cr_2O_7$ (Cr VI) on lettuce, tomato and oats grown in a growth chamber from seed for 14 days. The $EC_{50}$ values for lettuce, tomato and oats were 0.16, 0.29, and 1.4 ppm Cr.

Wang (1994) evaluated the effects of several metals and organic compounds on radicle weight of rice seed germinated and grown for 6 d in solution. The calculated $EC_{50}$ for Cr (VI) (K2CrO4) was 4.8 ppm.

Moral et al. (1995) measured 24 and 32% reductions in root length and fresh root weight of tomato seedlings grown in nutrient solution containing 100 ppm Cr (III) as $CrCl_3$. Chromium at 50 ppm had no effect.

Top weight of soybean seedlings grown for 5 d in nutrient solution containing Cr(VI) was reduced 21% by 1 ppm Cr, while 0.5 ppm had no effect (Turner and Rust, 1971).

Wallace et al. (1977a) measured a 30% reduction in leaf weight of bush beans grown 11 d in nutrient solution containing 0.54 ppm Cr as Cr(VI) ($K_2Cr_2O_7$).

Length of the longest root of rye grass was reduced 69% by exposure to 2.5 ppm Cr(VI) ($K_2Cr_2O_7$; lowest concentration tested) in nutrient solution (pH 7) for 14 d (Wong and Bradshaw, 1982). Length of the longest shoot was not affected at this concentration.

Breeze (1973) found little difference in the toxicity of Cr(III) [$Cr_2(SO_4)_3$] and Cr(VI) ($K_2Cr_2O_7$) to rye grass seed germination. Seed exposed to solutions containing 50 ppm Cr (III) or (VI) reduced germination 37 and 38% after 2.5 days.

Nutrient solution containing 0.05 ppm Cr(III) [$Cr_2(SO_4)_3$] reduced leaf and stem weights of chrysanthemum seedlings exposed for 21 days by 31 and 36% (Patel et al., 1976). This was the lowest concentration tested and root weight was not affected.

Using a 1:1 combination of Cr(III) ($CrCl_3$) and Cr(VI) ($K_2CrO_7$) in nutrient solution (pH 5), Hara et al. (1976) measured a 68% reduction in weight of cabbage with 10 ppm Cr. Chromium at 2 ppm had no effect.

The concentrations of Cr(VI), from $(NH_4)_2CrO_4$, required for a 50% reduction in seed germination and root length of mustard after a 3-day exposure in solution (pH 7.3), was reported by Fargasova (1994). $LC_{50}$ for germination was 100 ppm and $EC_{50}$ for root length was 46 ppm Cr.

Confidence in the solution Cr benchmark of 0.05 ppm is moderate, however the concentration approximating the 10th percentile was the lowest concentration tested and caused a greater than 30% reduction in the growth parameter.

**Mechanism of phytotoxicity**. Chromium is not an essential element in plants. The (VI) form is more soluble and available to plants than the (III) form and is considered the more toxic form (Smith et al. 1989). In soils within a normal Eh and pH range, Cr(VI), a strong oxidant, is likely to be reduced to the less available Cr(III) form although the (III) form may be oxidized to the (VI) form in the presence of oxidized Mn (Bartlett and James 1979). In nutrient solution, however, both forms are about equally taken up by plants and toxic to plants (McGrath 1982). Cr(VI), as $CrO_4^{2-}$, may share a root membrane carrier with $SO_4^{2-}$. Cr(VI) is more mobile in plants than Cr(III) but translocation varies with plant type. After plant uptake it generally remains in the roots because of the many binding sites in the cell wall capable of binding especially the Cr(III) ions (Smith et al. 1989). Within the plant Cr(VI) may be reduced to the Cr(III) form and complexed as an anion with organic molecules. Symptoms of toxicity include stunted growth, poorly developed roots, and leaf curling. Chromium may interfere with C, N, P, Fe, and Mo metabolism, and enzyme reactions (Kabata-Pendias and Pendias 1984).

### 3.1.11 Cobalt

**Experiments conducted in soil.** There was no primary reference data showing toxicity of Co to plants grown in soil. Kabata-Pendias and Pendias (1984) reported unspecified toxic effects on plants grown in a surface soil with the addition of 20 ppm Co. We have low confidence in the benchmark based on this study alone.

**Experiments Conducted in Solution**. Wallace et al. (1977a) evaluated the effect of Co as $CoSO_4$ on bush beans grown for 21 d in nutrient solution. Leaf dry weight was reduced 22% by the addition of 0.06 ppm Co, the lowest concentration tested. Root and stem weights were not affected at this concentration. Chrysanthemum seedling root weight was reduced 55% after 21 days of growth in nutrient solution containing the same concentration of Co as $CoSO_4$ (Patel et al. 1976). Leaf and stem weight were not affected at this concentration.

Misra et al. (1994) evaluated the effects of several metals on seed germination and root growth of broad bean (*Vicia faba*). Seed germination was not affected by Co ($CoCl_2$) at concentrations up to 10 ppm Co in nutrient solution. Root elongation of plants exposed for 3 days to 10 ppm Co was reduced 30%, while 8 ppm had no effect.

Patterson and Olson (1983) evaluated the effect of several metals in solution (pH 5 to 6) on white spruce (*Picea glauca*), black spruce (*Picea mariana*), paper birch (*Betula papyrifera*), jack pine (*Pinus banksiana*), white pine (*Pinus strobus*), red pine (*Pinus resinosa*), and honeysuckle (*Lonicera tatarica*) grown from seed for 5 to 21 d. There was no clear relationship between general tree group (i.e., spruce or pine) and effect of Co on radicle elongation. Toxic concentrations ranged from 5 ppm (35 and 47% reductions in honeysuckle and paper birch) to 100 ppm (53% reductions in white pine). The other species were intermediate in their response to Cu in solution.

Confidence in the solution benchmark of 0.06 ppm Co is low because it is based on a limited number of types of plants.

**Mechanism of phytotoxicity**. Cobalt is not known to be essential to plants except legumes in symbiosis with $N_2$-fixing microorganisms. When translocated from roots it travels in the xylem as the Co(II) ion (Tiffin 1967). Toxicity symptoms due to excess Co are typical of Fe deficiency induced chlorosis and necrosis, and root tip damage (Wallace et al. 1977a). There appears to be inhibition of mitosis and chromosome damage (Aller et al. 1990).

### 3.1.12 Copper

**Experiments conducted in soil.** Miles and Parker (1979b) found approximately 68% reductions in root and shoot weights of little bluestem grown from seed for 12 weeks in a sandy soil (pH 7.8, % organic matter 2.5, CEC 12 meq/100g soil), when 100 ppm Cu as $CuSO_4$ was added. This was the only concentration tested. Growth was reduced in a second sandy soil (pH 4.8, % organic matter 1.9, CEC 6 meq/100g soil) by 86% with the addition of 100 ppm Cu (only concentration tested).

Wallace et al. (1977b) evaluated the effects of Cu, added as $CuSO_4$ to a loam soil, on leaf and stem weights of bush beans grown from seed for 17 days. Leaf weight was reduced 26% by 200 ppm Cu, while 100 ppm had no effect.

Confidence is low in the benchmark of 100 ppm Cu in soil because it is derived from fewer than 10 values.

**Experiments in solution.** The effect of Cu on stem diameter increase and plant weight of red pine, maple (*Acer rubrum*), dogwood (*Cornus stolonifera*), and honeysuckle was examined by Heale and Ormrod (1982). All seedlings (90-d old) grown for 110 d in nutrient solution containing 4 ppm Cu from $CuSO_4$ (lowest concentration tested) were affected. Reductions in rate of stem diameter increase and in plant weight were 41 and 50%, 79 and 67%, and 97 and 74% for maple, dogwood, and honeysuckle, respectively. Red pine experienced a 28% decease in plant weight at 4 ppm Cu but the stem diameter increase was unaffected up to 20 ppm Cu (highest concentration tested).

Mocquot et al. (1996) investigated the toxicity of copper (as $CuSO_4$) to maize (*Zea mays*) seedlings in solution. At 0.64 ppm of copper, shoot length and root mass were decreased by about 23% and 42%, respectively. At 0.45 ppm of Cu, no toxicity was observed.

Patterson and Olson (1983) evaluated the effect of several metals in solution (pH 5 to 6) on white spruce, black spruce, paper birch, jack pine, white pine, red pine, and honeysuckle grown from seed for 5 to 21 d. Paper birch, which was least tolerant of Co, was also most affected by Cu, with a 39% reduction in radicle elongation at 1 ppm Cu. As in the case of Co, white pine was the most tolerant plant tested with a 42% reduction in radicle elongation at 100 ppm Cu. The other species were intermediate in their response to Cu in solution.

Wang (1994) evaluated the effects of several metals and organic compounds on radicle weight of rice seed germinated and grown for 6 d in solution. The calculated $EC_{50}$ for Cu ($CuCl_2$) was 0.22 ppm.

Wong and Bradshaw (1982) measured reductions in lengths of longest roots and shoots of rye grass grown for 14 d in nutrient solution (pH 7) to which Cu as $CuSO_4$ was added. The length of the longest root was reduced 71% by 0.031 ppm Cu, the lowest concentration tested.

Maize seedlings germinated and grown for 10 d in solution containing $CuSO_4$ had a 40% reduction in total fresh weight in the 0.06 ppm Cu treatment (lowest concentration tested) (Stiborova et al. 1986). This same concentration caused a 45% reduction in root weight of chrysanthemums grown for 21 d in nutrient solution with $CuSO_4$ added (Patel et al. 1976). Leaf and stem weights were not affected.

Gupta and Mukherji (1977) evaluated the effect of Cu as a $CuSO_4$ solution on rice seedling shoot and root lengths. After 4 days, root length was reduced 64% by 64 ppm Cu, while 6.4 ppm had no effect.

Confidence in the solution benchmark for Cu, 0.06 ppm, is moderate; however it is based on a limited number of types of plants.

**Mechanism of Phytotoxicity**. Copper is a micronutrient essential for plant nutrition. It is required as a co-factor for many enzymes and is an essential part of a copper protein involved in photosynthesis. Copper occurs as part of enzymes and enzyme systems. Root absorption appears to be passive, perhaps in organo-copper complexes (Jarvis and Whitehead 1983), and active through a specific carrier (Fernandes and Henriques 1991). Copper may be deficient in low-copper soils because the metal is adsorbed to cells in the root system. The form in which it is taken into the root affects its binding there (Wallace and Romney 1977b). Copper can be transported in the xylem and phloem of plants complexed with amino acids.

The most common toxicity symptoms include reduced growth, poorly developed root system, and leaf chlorosis (Wong and Bradshaw 1982). The basic deleterious effect of Cu is related to the root system where it interferes with enzyme functioning (Mukherji and Das Gupta 1972). It also strongly interferes with photosynthesis and fatty acid synthesis (Smith et al. 1985).

### 3.1.13 Fluorine

**Experiments conducted in soil**. The benchmark is based on a report of unspecified reductions in plant growth in a surface soil with the addition of 200 ppm F (Kabata-Pendias and Pendias 1984). Confidence in the benchmark for F is low because it based on this reference alone.

**Experiments conducted in solution**. Bowen (1979) reported unspecified reductions in plant growth in a solution culture with the addition of 5 ppm F. We have low confidence in the benchmark based on this study alone.

**Mechanism of Phytotoxicity**. Fluorine is not an essential plant element. Toxicity symptoms are the same as seen in plants exposed to HF gas; marginal leaf chlorosis and interveinal chlorosis (Brewer 1966).

### 3.1.14 Iodine

**Experiments conducted in soil**. Newton and Toth (1952) measured the effects of I, added to soils (pH 6.8) as KI at 0.4 and 4 ppm, on top weight of tomatoes grown from seed for 97 days. They found a 47% reduction in top weight in a sandy soil, 25% in one loam soil and 52% in another, and 30% reduction in top weight in a silt loam soil at 4 ppm I.

The benchmark of 4 ppm is taken from this study. Confidence in this benchmark is low.

**Experiments conducted in solution**. Top weight of corn seedlings grown for 60 days in nutrient solution (pH 5.8) was reduced 31% by the addition of 0.5 ppm I added as KI (Lewis and Powers 1941). Iodine at 0.1 ppm had no effect on plant growth.

Newton and Toth (1952) measured the effects of I, added to nutrient solution as KI at 0.5 and 5 ppm, on top weight of tomato seedlings grown for 60 days. Iodine at 5 ppm reduced top weight 46%, while 0.5 ppm had no effect.

Confidence in the solution benchmark of 0.5 ppm I is low because of the limited amount of data on which it is based.

**Mechanism of phytotoxicity.** Iodine is not known to be essential for plant growth. It is present in available form in very small amounts in soil. Toxicity symptoms are similar to salt burn, that is, burning of leaf edges and subsequent leaf necrosis (Martin 1966b).

### 3.1.15 Iron

**Experiments conducted in soil.** No information was found on which to base a toxicity benchmark for plants growing in soil.

**Experiments conducted in solution.** Wallihan (1966) reported unspecified reductions in plant growth in a solution culture with the addition of 10 ppm Fe. Wallace et al. (1977b) evaluated the effects of Fe (as $FeSO_4$) on leaf, stem, and root weights of bush bean seedlings grown for 15 days in nutrient solution. Iron at 28 ppm reduced all three measures 67, 52, and 67%, respectively, while 11.2 ppm had no effect.

After 55 days cabbage seedling plant weight was reduced 45% by 50 ppm Fe added as $FeSO_4$ to nutrient solution (pH 5), while 10 ppm had no effect on growth (Hara et al. 1976).

Confidence in the benchmark for Fe in solution (10 ppm) is low because it is based on less than 10 values.

**Mechanism of phytotoxicity.** Iron is the key metal required for energy transformations needed for cellular functioning. It occurs in heme and nonheme proteins and is concentrated in chloroplasts. Organic Fe complexes are involved in photosynthetic electron transfer. Plant symptoms of toxicity are not specific and differ among plant species and growth stages (Foy et al. 1978).

### 3.1.16 Lead

**Experiments conducted in soil.** Rolfe and Bazzaz (1975) measured the effects of Pb, added to a 1:1:1 mixture of soil, sand and peat moss as $PbCl_2$, on 1-year-old seedlings of autumn olive (*Elaeagnus umbellata*) grown for 49 days. They found a reduction in transpiration of approximately 25% with the addition of 160 ppm Pb, while 80 ppm had no effect.

Dixon (1988) measured the response of red oak seedlings grown for 16 weeks in a sandy loam soil (pH 6, % organic matter 1.5) with addition of Pb ($PbCl_2$). Lead at 50 ppm reduced tree weight by 26%, while 20 ppm had no effect.

Carlson and Bazzaz (1977) measured foliage biomass, trunk diameter, and new stem and root growth reductions in 2- to 3-year-old American sycamore saplings associated with a 90-day exposure to Pb as $PbCl_2$ added to a silty clay loam soil. The lowest concentration tested (50 ppm Cd) was responsible for a 30% reduction in leaf weight.

Burton et al. (1984) grew Sitka-spruce seedlings from 4 weeks of age in a mixture of acidic peaty gley soil and sand with Pb added as $PbCl_2$. Lead added at 100 ppm resulted in a reduction of about 25% in root and shoot weight of the 18-week old seedlings.

Miles and Parker (1979b) found approximately 52% reductions in root and shoot weights of little bluestem grown from seed for 12 weeks in a sandy soil (pH 7.8, % organic matter 2.5, CEC 12 meq/100g soil), when 450 ppm Pb as $PbCl_2$ was added. This was the only concentration tested. Root growth was reduced in a second sandy soil (pH 4.8, % organic matter 1.9, CEC 6 meq/100g soil) by 22% with the addition of 450 ppm Pb (only concentration tested).

Carlson and Rolfe (1979) found that 5000 ppm Pb added as $PbCl_2$ to a soil was necessary to give 46 and 31% reductions in clipping weight of ryegrass and fescue (*Festuca rubra*) grown in a silt loam soil (pH 5.9, CEC 21 meq/100g soil) from seed.

Muramoto et al. (1990) measured the effects of addition of Pb as PbO to an alluvial soil (pH 6) on growth and yield of wheat grown from seed to maturity. Root weight was reduced 22% by 1000 ppm Pb, while 300 ppm had no effect.

In a study using Brown earth soil, Khan and Frankland (1984) investigated the effects of Pb added as $PbCl_2$, the less soluble PbO, or a combination, on root weight of wheat and oats. Wheat root weight was reduced 34% by the addition of 1000 ppm Pb as $PbCl_2$, while 500 ppm had no effect. Oat growth was reduced 37% by the addition of 500 ppm Pb as $PbCl_2$, while 100 ppm had no effect. Wheat and oats were grown from seedlings for 42 days.

Hassett et al. (1976) measured a 48% reduction in corn root length after 7 days of growth from seed in a loamy sand soil (pH 6.5, % organic matter 2, CEC 2 meq/100g soil) to which 500 ppm (as $PbCl_2$) was added. Lead at 250 ppm did not affect growth.

Corn (*Zea mays* L.) grown from seed for 31 days in a loamy sand used in the 1976 work (pH 6, CEC 2 meq/100g soil) experienced a 42% decrease in plant weight after addition of 250 ppm Pb (Miller et al., 1977). Lead at 125 ppm did not affect growth.

In a study using Brown earth soil, Khan and Frankland (1983) investigated the effects of Pb added as $PbCl_2$, the less soluble PbO, or a combination, on radish root and top weights. Radish root growth was reduced 24% by the addition of 500 ppm Pb as $PbCl_2$, or 1000 ppm (lowest concentration tested) as PbO (27% reduction), to a soil having a pH of 5.4. Plants were grown from seed for 42 days.

John and Van Laerhoven (1972) investigated the effects of lead, added in various forms, to a silty clay loam soil (pH 3.8, % organic matter 17, CEC 45 meq/100g soil). Lettuce was grown from seed for 30 days before tops were harvested. Lead added at a rate 1000 ppm (lowest concentration tested) as $PbCl_2$ and $Pb(NO_3)_2$ reduced plant weight by 35 and 25%.

Moderate confidence is assumed for the 50 ppm benchmark for Pb because it is based on 17 values from experiments conducted with a range of different plant species.

**Experiments conducted in solution**. The effect of Pb, as $PbCl_2$, on root elongation of 3-week-old Norway spruce seedlings grown for 7 days in nutrient solution (pH 4) was examined by Lamersdorf et al. (1991). The only concentration tested, 0.02 ppm Pb, reduced root elongation by 26%.

Godbold and Kettner (1991) measured a 24% reduction in rate of root elongation of 3-wk old Norway spruce seedlings grown in a nutrient solution (pH 4) containing 0.2 ppm Pb ($PbCl_2$; lowest concentration tested) for 7 d.

The rate of root growth of onions grown for 4 d in a solution containing lead as $Pb(NO_3)_2$ was reduced 33% by 0.2 ppm Pb, while 0.02 ppm had no effect (Liu et al. 1994).

Wang (1994) evaluated the effects of several metals and organic compounds on radicle weight of rice seed germinated and grown for 6 d in solution. The calculated $EC_{50}$ for Pb $[Pb(C_2H_3O_2)_2]$ was 9.7 ppm.

Mhatre and Chaphekar (1982) tested several species at germination stage for their response to Pb. Seeds of sorghum, alfalfa, mung bean, cluster bean, and radish were allowed to germinate in solutions containing 0.001, 0.01, 0.1, or 1 ppm Pb as $Pb(NO_3)_2$. Germination counts after 24 hours showed no effect of Pb. After 5 days, root length of cluster bean was reduced 34% by 0.001 ppm Pb. Root length of alfalfa was reduced 25% by the addition of 0.1 ppm. Root and shoot lengths of radish were reduced 27 and 32% by the addition of 1 ppm Pb. Root length of mung bean was reduced 23% by the addition of 1 ppm.

The effect of Pb on root length of barley and maize seedlings after a 7-day exposure in nutrient solution was examined by Wierbicka and Antosiewicz (1993). Root length of maize was reduced 25% by 1 ppm Pb (lowest concentration tested) and that of barley reduced 27% by 2 ppm Pb, while 1 ppm had no effect.

Wong and Bradshaw (1982) evaluated the effect of Pb on root and shoot elongation of rye grass grown in solution (pH 7) with Pb added as $Pb(NO_3)_2$. After 14 days they found 77 and 36% reductions in lengths of the longest roots and shoots in response to 2.5 ppm Pb (lowest concentration tested).

Wong and Lau (1985) evaluated the effect of Pb on root length of several cultivars of Bermuda grass and wire grass (*Eleusine indica* L.) grown in solution with Pb added as $Pb(NO_3)_2$. After 14 days they found root length of all Bermuda grass cultivars reduced an average of 64% in response to 10 ppm Pb (lowest concentration tested). The response of wire grass was more variable with 75 and 27% reductions in root length at 10 ppm for two cultivars, and a 87% reduction at 20 ppm for the third (10 ppm had no effect).

Hooper (1937) ran a series of experiments to evaluate the effect of Pb as $PbSO_4$ on fresh weight of french beans grown in nutrient solution. In three of the runs she found an average 32% reduction in response to 10 ppm Pb, while 5 ppm had no effect. In two other runs, fresh weight was reduced approximately 25% by 30 ppm, while 20 ppm Pb had no effect.

The fresh weight of maize seedlings grown for 10 days in a Pb-containing solution $(Pb(NO_3)_2$ was reduced 45% by 207 ppm Pb, while 20.7 ppm had no effect (Stiborová et al. 1986).

The concentrations of Pb, from $Pb(CH_3COO)_2$, required for a 50% reduction in seed germination and root length of mustard after a 3-day exposure in solution (pH 5.5), was reported by Fargasova (1994). LC50 for germination was 1148 ppm and $EC_{50}$ for root length was 263 ppm Pb.

Confidence in the 0.02 ppm toxicity benchmark for plants growing in solution is moderate.

**Mechanism of phytotoxicity**. Lead is taken up passively by roots and translocation to shoots is limited (Wallace and Romney 1977b). It is bound to the outside of roots, in the apoplast, and in cell walls and organelles of absorbing roots (Koeppe 1981). In the plant, lead may exist in naturally chelated form, or in pyro- or orthophosphate forms. The phytotoxicity of lead is relatively low compared with other trace elements. It affects mitochondrial respiration and photosynthesis by disturbing electron transfer reactions (Miles et al. 1972).

### 3.1.17 Lithium

**Experiments conducted in soil.** Wallace (1979) investigated the effects of Li ($Li_2C_2O_4$) added to a loam soil (pH 6) on barley seedlings grown for 10 days. Lithium at 500 ppm (lowest concentration tested) resulted in a 66% reduction in shoot weight.

Wallace et al. (1977c) measured the reduction in leaf and stem weights of cotton and bush bean seedlings resulting from additions of Li, as LiCl or $LiNO_3$, to a loam soil (pH 6). Cotton leaf and stem weights were reduced 33 and 56% by the addition of 50 ppm Li as $LiNO_3$, while 25 ppm had no effect. Bush bean leaf weight was reduced 32% by the addition of 25 ppm Li as LiCl, while 10 ppm had no effect. Cotton was exposed for 16 days and bush beans for 10 days.

Aldrich et al. (1951) recorded an undefined phytotoxic effect on sweet orange seedlings grown in a surface soil for 6 months with 2 ppm Li as $LiSO_4$ (lowest concentration tested).

Confidence in the benchmark of 2 ppm is low.

**Experiments conducted in solution.** Wallace et al. (1977c) measured the reduction in leaf, stem, and root weights of bush bean seedlings resulting from additions of Li, as $LiNO_3$, to nutrient solution. Stem weight was reduced 30% by 3.5 ppm Li, the lowest concentration tested.

Confidence in the 3 ppm toxicity benchmark for plants growing in solution is low.

**Mechanism of phytotoxicity.** The soluble Li in soils is easily taken up by plants. It appears to share the $K^+$ transport carrier and is mainly found in leaf tissues. Toxicity symptoms include damage to root tips and necrosis of interveinal leaf tissue (Aldrich et al. 1951).

### 3.1.18 Manganese

**Experiments conducted in soil.** Wallace et al. (1977b) evaluated the effects of Mn, added as $MnSO_4$ to a loam soil, on leaf and stem weights of bush beans grown from seed for 17 days. Stem weight was reduced 29% by 500 ppm Mn (lowest concentration tested).

Because the 500 ppm benchmark for Mn is based on this one study, confidence in it is low.

**Experiments conducted in solution.** Langheinrich et al. (1992) evaluated effects of solution pH, N supply and Mn ($MnSO_4$) on growth parameters of Norway spruce seedlings. In an experiment run at pH 6 for 32 d, root growth was measured (length and weight). Manganese added at 44 ppm (lowest concentration tested) reduced root growth 50% when N was added as $NH_4$, and reduced root length by 37% when N was added as $NO_3$ (11 pm had no effect). In experiments run at pH 4 for 77 days, epicotyl height, length of the primary root, and percent plants with terminal buds were determined. Manganese added at 44 ppm (only concentration tested) reduced all measures approximately 40% when N was added as $NO_3$ and reduced height of epicotyl and percent plant with terminal buds by approximately 55% when N was added as $NH_4$.

Wong and Bradshaw (1982) evaluated the effect of Mn on root and shoot elongation of rye grass grown in solution (pH 7) with Mn added as $MnSO_4$. After 14 days, they found a 71% reduction in the length of the longest root in response to 0.75 ppm (lowest concentration tested).

Wallace et al. (1977b) evaluated the effect of Mn (as $MnSO_4$) on leaf, stem, and root weights of bush bean seedlings in grown in nutrient solution. After 16 days, in one experiment, the three weights were reduced approximately 25% by 5.5 ppm Mn, the lowest concentration tested. In a second, 21-day experiment, the three weights were reduced approximately 40% by 55 ppm, while 5.5 ppm Mn had no effect.

LeBot et al. (1990) evaluated the effect of Mn, as $MnSO_4$, on weight of tomato plants growing in nutrient solution (pH 5.5) for 17 days. Manganese at 5.5 ppm reduced plant weight by 27%, while 2.8 ppm had no effect.

Foy et al. (1995) evaluated the effect of pH and plant genotype on the toxicity of Mn ($MnSO_4$) on 9-d old seedlings of cotton grown in nutrient solution for 18 d. Leaf and root dry weights of one genotype were reduced approximately 25% at 8 ppm in the pH 5 solution, while in the pH 4.6 solution, Mn was not toxic until a concentration of 16 ppm was reached (35 to 77%) reductions). For the second genotype, the lowest concentration of Mn tested (4 ppm) reduced plant weight approximately 35% at both pH levels.

Wang (1994) evaluated the effects of several metals and organic compounds on radicle weight of rice seed germinated and grown for 6 d in solution. The calculated $EC_{50}$ for Mn ($MnCl_2$) was 100 ppm.

Burke et al. (1990) compared the effects of 30 days of hourly root submersion in an Mn in solution ($MnSO_4$, pH 4.8) on root and shoot weights of five wheat cultivars. For three of the five cultivars, root weight was reduced an average of 43% (25 to 60%) by the addition of 30 ppm Mn, the lowest concentration. This concentration reduced both root and shoot weight of a fourth cultivar by 25%. The fifth cultivar experienced 60 and 35% reductions in root and shoot weight with the addition of 90 ppm Mn, while 30 ppm had no effect.

The effect of Mn on weight of potato (*Solanum tuberosum* L.) shoots grown for 32 days in nutrient solution was examined by Marsh and Peterson (1990). A concentration of 33.5 ppm (lowest concentration tested) caused a 23% reduction in shoot weight.

Confidence in the solution Mn benchmark of 4 ppm is moderate.

**Mechanism of phytotoxicity**. Manganese is essential for plant growth. It is involved in N assimilation, as a catalyst in plant metabolism and functions with Fe in the synthesis of chlorophyll (Labanauskas 1966). Toxicity symptoms include marginal chlorosis and necrosis of leaves and root browning. Excess Mn interferes with enzymes, decreases respiration, and is involved in the destruction of auxin (Foy et al. 1978). It is fairly uniformly distributed between roots and shoots (Wallace and Romney 1977b).

### 3.1.19 Mercury

**Experiments conducted in soil.** There were no primary reference data describing toxicity of Hg to plants grown in soil. Kabata-Pendias and Pendias (1984) report unspecified toxic effects on plants grown in a surface soil with the addition of 0.3 ppm Hg.

Panda et al. (1992) evaluated the phytotoxicity of mercury from the solid waste deposits of a chloralkali plant. After exposure of barley to mercury waste for 7 days, seedling height was reduced by 19% at 64 ppm mercury in soil. Germination of barley was reduced by 20% at 103 ppm. The NOEC was 34.9 ppm. The authors did not apparently test the waste for contaminants other than mercury. However, mercury was the major contaminant in the waste, at 2550 mg/kg.

Confidence in the inorganic mercury benchmark of 0.3 ppm is low because it is based on a secondary reference, and the toxicity threshold in the chloralkali study was more than two orders of magnitude higher.

**Experiments conducted in solution.** The effect of Hg, as $HgCl_2$, on root elongation of 3-week-old Norway spruce seedlings grown for 7 days in nutrient solution (pH 4) was examined by Lamersdorf et al. (1991). The only concentration tested, 0.002 ppm Hg, reduced root elongation by 31%. Methyl mercury ($Ch_3HgCl$) completely stopped root elongation at a concentration of 0.0002 ppm, the only concentration tested.

Al-attar et al. (1988) investigated the effect of mercury (II) acetate on the length and weight of the roots and shoots of perennial ryegrass (*Lolium perenne*) seedlings in solution. This study was not used in the derivation of the benchmark for inorganic mercury or methyl mercury, but it is included here as an example of a toxicity test using mercury. A concentration of 0.0005 ppm of mercury (II) resulted in a 29% reduction in root dry weight, a 24% decrease shoot dry weight, and a 2% decrease in root length. The NOEC was 0.0001 ppm.

Schlegel et al. (1987) investigated the effects of inorganic ($HgCl_2$) and organic ($CH_3HgCl$) Hg on needle chlorophyll content, transpiration rate, and $CO_2$ uptake of 2-week-old spruce seedlings in nutrient solution (pH 4.3) for 35 days. Methyl Hg at 0.002 ppm Hg (lowest concentration tested) reduced transpiration rate and $CO_2$ uptake by 49, and 73%. At 0.02 ppm Hg (lowest concentration tested), both forms reduced needle chlorophyll content approximately 28%.

Godbold and Huttermann (1985) measured a 64% reduction in root elongation rate of 4-wk old Norway spruce seedlings grown in a nutrient solution (pH 4.3) containing 0.02 ppm Hg ($HgCl_2$; lowest concentration tested) for 7 d.

Suszcynsky and Shann (1995) measured 50% reductions in root and shoot dry weights of 5-wk old tobacco (Nicotiana miersii) seedlings grown in nutrient solution (pH 6) containing 1 ppm Hg as $HgCl_2$. Mercury at 0.1 ppm had no effect.

Mhatre and Chaphekar (1982) tested several species at germination stage for their response to Hg. Seeds of sorghum, alfalfa, mung bean, cluster bean, and radish were allowed to germinate and grow for 5 days in solutions containing 0.001, 0.01, 0.1, or 1 ppm Hg as $HgCl_2$. At 0.01 ppm Hg, root length reductions ranged from 22 for radish to 52% for alfalfa, with Pennisetum, mustard, sorghum, and cluster bean having intermediate reductions. Shoot length of Pennisetum, alfalfa, and cluster bean were also reduced at this concentration 25, 37, and 26%, respectively. Root length of pea was reduced 40% by the addition of 0.1 ppm. Root and shoot lengths of mung bean were reduced 28 and 50% at this concentration.

Mukhiya et al. (1983) compared the toxicity of different Hg compounds to barley root and shoot length, and plant weight in solution at concentrations of 1, 5, 10, and 50 ppm and found organic forms to be more toxic than inorganic forms. After 7 days, mercury as $C_8H_8HgO_2$ (phenyl mercuric acetate) at 5 ppm reduced shoot length and plant weight 27 and 25%. Mercuric acetate ($C_4H_6HgO_4$) at 10 ppm Hg reduced root length and plant weight 23%. Mercurous chloride ($Hg_2Cl_2$) at 50 ppm reduced root length and plant weight 22 and 25%, and 50 ppm mercuric chloride ($HgCl_2$) reduced plant weight 25%, root length 28%, and shoot length 35%.

The concentrations of Hg, from $HgCl_2$, required for a 50% reduction in seed germination and root length of mustard after 3 days of exposure in solution (pH 7.4), was reported by Fargasova (1994). LC50 for germination was 129 ppm and $EC_{50}$ for root length was 9.3 ppm Hg.

After 14 days, lengths of longest root and shoot of germinating rye grass seedlings were reduced 40 and 23% by 5 ppm Hg (lowest concentration tested) added to nutrient solution (pH 7) as $HgCl_2$ (Wong and Bradshaw, 1982).

Confidence in the solution phytotoxicity benchmark for inorganic mercury (0.005 ppm) is moderate because it is based on 17 values and a range of plant species.

Confidence in the solution phytotoxicity benchmark for organic mercury (0.002 ppm Hg) is low because it is based on less than 10 values. Furthermore, the concentration approximating the 10th percentile was the lowest concentration tested and caused a 100% reduction in the growth parameter.

**Mechanism of Phytotoxicity**. Mercury and its compounds taken up by roots are translocated to only a limited extent in plants. Organic forms of Hg may be translocated to a greater degree than inorganic forms in some plants (Huckabee and Blaylock 1973). Gay (1975) reports that pea plants (*Pisum sativum*) form methyl mercury as an intermediate product from Hg added to the soil in organic and inorganic forms.

### 3.1.20 Molybdenum

**Experiments conducted in soil**. Kabata-Pendias and Pendias (1984) reported unspecified toxic effects on plants with the addition of 2 ppm Mo. Confidence in the benchmark of 2 ppm, based on this study alone, is low. Because the bioavailability of molybdenum increases with pH, toxicity would also likely increase with pH (unlike many metals). Neuman et al. (1987) assert that phytotoxicity of molybdenum in the field has never been recorded. Also, molybdenum is required by the nitrogenase of nitrogen-fixing microorganisms; thus, legumes are sometimes fertilized with the element. Although studies of molybdenum fertilization have been undertaken, none of these studies use molybdenum added to soil at a concentration of 2 ppm or above. Aghatise and Tayo (1994) observed slight increases in many growth parameters of soybean (*Glycine max*) with fertilization with molybdenum up to 0.8 kg/ha (about 0.5 mg/kg if 15 cm incorporation depth is assumed).

**Experiments conducted in solution**. Wallace et al. (1977b) evaluated the effect of Mo (as $H_2MoO_4$) on root, leaf, and stem weights of bush bean seedlings in nutrient solution. After 14 days, leaf weight was reduced 36% by 9.6 ppm Mo, the lowest concentration tested.

Wallace (1979) measured a 35% decrease in leaf weight of bush bean when grown for 14 days in nutrient solution (pH 5) with 5.7 ppm Mo (as $H_2MoO_4$), the lowest concentration tested. Root weight was not affected at this concentration.

Johnson (1966) reported unspecified toxic effects on plants grown in a solution with the addition of 0.5 ppm Mo.

Saco et al. (1995) observed in a fertilization experiment that 1 ppm of molybdenum did not affect nitrate and nitrite reductase activity, increased ammonium and nitrite content of the leaves and protein content in the root, and produced spots on the leaves. This quantity is not included in the derivation of the benchmark because other growth-related studies have been obtained.

Confidence in the 0.5 ppm benchmark for toxicity to plants growing in solution culture is low because it is based on fewer than 10 values.

**Mechanism of Phytotoxicity**. Molybdenum is required for symbiotic $N_2$ fixation by legumes and for growth of nonleguminous plants. The most important functions of Mo in plants are related to enzymes active in N metabolism (activation of nitrogenase and nitrate reductase). The majority of Mo taken up by the root system tends to remain in the roots although significant amounts may be translocated to the shoots in some cases (Wallace and Romney 1977b). Toxicity symptoms include chlorosis, apparently due to interference with Fe metabolism (Warington 1954).

### 3.1.21 Nickel

**Experiments conducted in soil**. Dixon (1988) measured the response of red oak seedlings grown for 16 weeks in a sandy loam soil (pH 6, % organic matter 1.5) with addition of Ni ($NiCl_2$). Nickel at 50 ppm reduced tree weight by 30%, while 20 ppm had no effect.

Khalid and Tinsley (1980) measured a 66% reduction in ryegrass shoot weight with the addition of 180 ppm Ni (as $NiSO_4$) to a loam soil (pH 4.7). Addition of 90 ppm Ni had no effect. Plants were grown 4 weeks from seed.

Oats grown from seed for 110 days in the presence of 50 ppm Ni (as $NiCl_2$) in soil (pH 6.1, CEC 6 meq/100 g, and % organic matter 1.4) had reductions of 38 and 63% in grain and straw weight (Halstead et al., 1969). In a second soil (pH 5.7, CEC 11.7 meq/100 g, % organic matter 4.1) only straw weight was reduced (45%) by addition of 100 ppm Ni (50 ppm had no effect).

Two cultivars of cotton were tested for tolerance to Ni in soil (Rehab and Wallace, 1978). Two-week-old seedlings grown for 35 days in soil (pH 6.8) to which 100 ppm Ni was added (lowest concentration tested) experienced reduced leaf and stem weights; 46 and 28% for the first cultivar, and 44 and 59% for the second.

Wallace et al. (1977d) report the results of experiments on the effects of Ni (as $NiSO_4$) on seedlings of a variety of plants grown in a loam soil at several pHs. Corn grown in soil at pH 4.2, 5.6, and 7.5 experienced 74, 80, and 50% reductions in shoot weight after 14 days of growth with the addition of 250 ppm Ni. Ni at 100 ppm had no effect. At pH 5.8, bush beans grown for 16 days had a 64% reduction in shoot weight with the addition of 100 ppm (lowest concentration tested). At pH 7.5, a 36% reduction in plant weight occurred with 250 ppm Ni, while 100 ppm had no effect. After 28 days of growth in a loam soil at pH 5.8, bush bean leaf weight was reduced 45% by the addition of 100 ppm Ni, while 25 ppm had no effect. For barley under these same growth conditions, 25 ppm Ni (lowest concentration tested) reduced shoot weight 88%.

Traynor and Knezek (1973) measured a 21% reduction in corn plant weight with the addition of 294 ppm Ni (as $NiCl_2$) to a sandy soil (pH 5, % organic matter 2, CEC 6 meq/100g soil) in which the plants had been grown for 5 weeks from seed. Addition of 220 ppm had no effect.

Confidence in the 30 ppm benchmark for Ni is low. Although there were 14 values, the concentration closest to the 10th percentile was the lowest concentration tested and caused an 88% reduction in the measured growth parameter. The next closest concentration was also responsible for a greater than 30% reduction in plant growth.

**Experiments conducted in solution**. The effect of Ni on stem diameter increase and plant weight of red pine, maple, dogwood, and honeysuckle was examined by Heale and Ormrod (1982). Seedlings (90-d from cutting) of red pine and honeysuckle grown for 110 days in nutrient solution containing 2 ppm Cu from $NiSO_4$ (lowest concentration tested) had reductions in stem diameter increase and plant weight of 100, and 25%, and 84 and 65%, respectively. Reductions in stem diameter increase in plant weight were 70% dogwood grown in solution containing 10 ppm Ni, while 2 ppm had no effect. Maple experienced a 48% decease in plant weight only at 10 ppm Ni with the stem diameter increase remaining unaffected up to 20 ppm Ni (highest concentration tested).

Patterson and Olson (1983) evaluated the effect of several metals in solution (pH 5 to 6) on white spruce, black spruce, paper birch, jack pine, white pine, red pine, and honeysuckle grown from seed for 5 to 21 d. Paper birch, which was least tolerant of Co and Cu, was also most affected by Ni, with a 21% reduction in radicle elongation at 1 ppm Ni. As in the case of Co and Cu, white pine was the most tolerant plant tested with a 24% reduction in radicle elongation at 50 ppm Ni. The other species were intermediate in their response to Ni in solution.

Misra et al. (1994) evaluated the effects of several metals on seed germination and root growth of broad bean (Vicia faba). Seed germination was not affected by Ni ($NiCl_2$) at concentrations up to 10 ppm Ni in nutrient solution. Root elongation in plants exposed for 3 days to 8 ppm Ni was reduced 30%, while 6 ppm had no effect.

Wang (1994) evaluated the effects of several metals and organic compounds on radicle weight of rice seed germinated and grown for 6 d in solution. The calculated $EC_{50}$ for Ni ($NiCl_2$) was 0.85 ppm.

Wong and Bradshaw (1982) measured a 29% decrease in length of longest root of rye grass when germinated and grown for 14 days in nutrient solution (pH 7) with 0.13 ppm Ni [$Ni(NH_4)_2(SO_4)_2$], the lowest concentration tested. Length of the longest shoot was unaffected at this concentration.

The effects of Ni, from $NiSO_4$, on germination and radicle length of radish, cabbage, turnip, lettuce, wheat, and millet after 3 days of growth in solution were determined by Carlson et al. (1991). There was no effect on seed germination up to 20 ppm Ni. Treatment levels were 0, 0.25, 0.5, 1, 2, 4, 8, 12, 16, and 20 ppm Ni. A concentration of 1 ppm reduced radicle length of lettuce and turnip by 24 and 25%. A concentration of 2 ppm reduced radicle length of cabbage by 30%. Eight ppm Ni reduced radicle length of radish by 32% and wheat by 45%, and 12 ppm caused a reduction in radicle length of millet by 40%.

Patel et al. (1976) found 26 and 27% decreases in leaf and stem weights of chrysanthemum seedlings when grown for 14 days in nutrient solution with 0.59 ppm Ni ($NiSO_4$), while 0.006 ppm had no effect. Root weight was not affected at 0.59 ppm Ni.

Wallace (1979) measured 92 and 68% decreases in root and leaf weights of bush bean seedlings when grown for 21 days in nutrient solution (pH 5) with 1.2 ppm Ni, the only concentration tested.

The effect of Ni, as $NiCl_2$, on plant weight of cotton grown in nutrient solution (pH 6) was evaluated by Rehab and Wallace (1978). Plant weight was reduced 92% by 5.9 ppm Ni, while 0.59 ppm had no effect.

Confidence in the 0.5 ppm phytotoxicity benchmark for Ni is high.

**Mechanism of Phytotoxicity**. Nickel is not generally considered to be an essential element for plants. However, it may be required by nodulated legumes for internal N transport as part of the urease enzyme (Aller et al. 1990). It is generally adsorbed as the Ni(II) ion and translocated in xylem and phloem with an organic chelate (Hutchinson 1981). Nickel is fairly uniformly distributed between roots and shoots (Wallace and Romney 1977b). Symptoms of Ni toxicity are generally Fe-deficiency induced chlorosis and foliar necrosis (Khalid and Tinsley 1980). Excess nickel affects nutrient absorption by roots, root development, and metabolism, and it inhibits photosynthesis and transpiration. Nickel can replace Co and other heavy metals located at active sites in metallo-enzymes and disrupt their functioning.

### 3.1.22 Selenium

**Experiments conducted in soil.** Wan et al. (1988) investigated the effects of Se(VI), as $Na_2SeO_4$, on alfalfa grown in three soils. In the sandy loam soil (pH 6.7, % organic matter 13) and in the two clay loam soils (pH 5.6, % organic matter 15; pH 6.9, % organic matter 13), shoot weight was reduced 83, 33, and 56% by the addition of 1.5 ppm Se(VI), while 0.5 ppm had no effect. Alfalfa was grown from seed to 0.25 bloom stage.

Singh and Singh (1978) investigated the toxicity of selenium (as $Na_2SeO_3$) to wheat (*Triticum aestivum*) in a sandy soil from India. The authors observed a 23% decrease in biomass as 50 days and a 22% decrease in biomass and a 28% decrease in grain yield at maturity (135 days) associated with the addition of the lowest concentration of selenium tested, 2.5 ppm.

The effect of Se(VI) ($Na_2SeO_4$) on alfalfa grown from seed to bloom was examined in five silty clay loam soils, ranging in pH from 6.9 to 7.8, by Soltanpour and Workman (1980). Shoot weight was reduced by 2 ppm in 4 of the 5 soils (91, 74, 23, and 27% reductions), with the greatest reductions in soils with the lowest organic matter content (%'s organic matter 3.1, 3.7, 5, and 6.5, respectively). Shoot weight was diminished 94% in the fifth soil (pH 7.0, % organic matter 6.3) with 4 ppm Se, 2 ppm having no effect.

Carlson et al. (1991) investigated the effects of Se(VI) (as $Na_2SeO_4$) and Se (IV) (as $Na_2SeO_3$) on sorgrass (*Sorghum vulgare*) grown from seed for 42 days in several soils. In a loamy sand soil (% organic matter 19, CEC 4 meq/100g soil) at pH 5.5 and 6.0, there were 59 and 53% reductions in shoot weight with the addition of 1 ppm Se(VI), (lowest concentration tested). No reductions were observed with additions of up to 4 ppm Se(IV). In a sandy soil (% organic matter 11, CEC 3 meq/100g soil) at pH 4.9, 1 ppm Se(VI) and 2 ppm Se(IV) caused 64 and 61% reductions in shoot weight. In this same sandy soil limed to pH 6.5, Se(IV) had no effect up to 4 ppm and Se(VI) reduced shoot weight 66% at 1 ppm.

Confidence in the 1 ppm benchmark for Se is low. Although there were 14 values, the concentration closest to the 10th percentile was the lowest concentration tested and consistently caused severe decreases in the measured growth parameter.

**Experiments conducted in solution.** Martin (1937a) evaluated the effect of Se (IV) from $Na_2SeO_3$ on root and shoot weight, and plant height of wheat and buckwheat (*Fagopyrum esculentum* L.) seedlings growing in nutrient solution for 42 days. Selenium at 1 ppm (lowest concentration tested) reduced wheat root and shoot weight, and plant height 41, 40, and 23%. This concentration also reduced buckwheat root and shoot weight, and plant height 59, 75, and 44%.

Wu et al. (1988) investigated the toxicity of selenium as sodium selenate to five grass species in nutrient solution. After 3 weeks of exposure, reduction in root length and shoot height was observed for: bermudagrass (*Cynodon dactylon*) at 0.5 ppm, the lowest concentration tested; crested wheatgrass (*Agropyron desertorum*) at 1 ppm; seaside bentgrass (*Agrostis stolonifera*) at 1 ppm; and buffalograss (*Buchloe dactyloides*) at 2 ppm. The reductions in root and shoot growth at the LOEC were about 40% and 50% for bermudagrass, 30% and 30% for crested wheatgrass, 20% and 25% for seaside bentgrass, and 70% and 50% for buffalograss. Toxicity to tall fescue (*Festuca arundinaceae*) at concentrations of selenium up to 2 ppm was not observed.

Banuelos et al. (1997) studied the effect of selenium (added as $NaSeO_4$) on nine "land races" of *Brassica juncea* (Indian mustard) and one race of *Brassica carinata* grown in solution culture. At 2 ppm of selenium, the lowest concentration tested, decreases in shoot yield of Indian mustard ranged from 12 to 23% and of root yield ranged from 11 to 34%. A 32% decrease in root yield of *Brassica carinata* was observed at the same 2 ppm concentration.

In experiments with plants found only in Se-rich soil, Trelease and Trelease (1938) found a 37% reduction in weight of milk-vetch (*Astragalus racemosus* L.) when grown in solution containing 27 ppm Se(IV) ($Na_2SeO_3$), while 9 ppm had no effect on growth.

Wallace et al. (1980) examined the toxicity of selenate-Se ($Na_2SeO_4$) on root and shoot weights of bush bean seedlings grown in nutrient solution (pH 4.4). Root weight was reduced 21% by 0.79 ppm Se, the lowest concentration tested, while shoot weight was unaffected.

Confidence in the 0.7 ppm phytotoxicity benchmark for Se is low because it is based on less than 10 values.

**Mechanism of phytotoxicity**. Selenium is not proven to be essential for plant growth. It is absorbed by plants as selenite, selenate or in organic form and the selenate may be the more toxic. It is believed that selenate is taken up actively while selenite uptake is largely passive (Peterson et al. 1981). Selenium is translocated to all parts of the plant, including the seed, in low molecular weight compounds (Broyer et al. 1972). Toxicity symptoms include chlorosis, stunting, and yellowing of the leaves. The mechanism of toxicity is thought to be indiscriminate replacement of S by Se in proteins and nucleic acids with disruptions in metabolism (Trelease et al. 1960). For example, selenomethionine is a less effective substrate than methionine for peptide bond formation, which could reduce protein synthesis (Eustice et al. 1981). Selenium-accumulating plant species incorporate less selenium into proteins than other species (Brown and Shrift 1981).

### 3.1.23 Silver

**Experiments conducted in soil**. There were no primary reference data showing toxicity of Ag to plants grown in soil. Confidence is low in the benchmark because it is based on a report of unspecified toxic effects on plants grown in a surface soil with the addition of 2 ppm Ag (Kabata-Pendias and Pendias 1984).

**Experiments conducted in solution**. Wallace (1979) examined the effect of Ag from $AgNO_3$ on shoot weight of bush bean seedlings grown in nutrient solution (pH 5) for 13 days. Silver at 0.16 ppm reduced shoot weight 58% while 0.016 ppm had no effect.

Wang (1994) evaluated the effects of several metals and organic compounds on radicle weight of rice seed germinated and grown for 6 d in solution. The calculated $EC_{50}$ for Ag ($AgNO_3$) was 0.55 ppm.

Confidence in the 0.1 ppm benchmark for toxicity to plants growing in solution is low due to lack of data.

**Mechanism of Phytotoxicity**. Silver taken up by plants remains in the root system precipitated with phosphate or chloride (Ward et al., 1979). The toxicity of Ag is related to the binding potential of $Ag^+$ ions to enzymes and other active molecules at cell surfaces (Cooper and Jolly 1970).

### 3.1.24 Technetium

**Experiments conducted in soil**. Wildung et al. (1977) investigated the effect of Tc on wheat and soybean grown in a silt loam soil (pH 6.8, % organic matter 1.4) from seed for 30 days. Addition of 1 ppm Tc as $TcO_4^-$, reduced shoot weight of wheat 100% and soybeans 99%, while 0.1 ppm had no effect.

Confidence in the benchmark of 0.2 ppm Tc is low because it is based on this study alone. The authors' chose to divide the LOEC by 5 because, although it was not expressed as such in the study, the severity of the effects seemed to border on mortality of the plants.

**Experiments conducted in solution**. Berlyn et al. (1980) conducted several experiments to examine the effect of Tc on fresh weight of soybean seedlings. When seedlings were germinated and allowed to grow for 20 days in nutrient solution containing 0.2 ppm Tc ($TcO_4^-$), plant weight was reduced 31%. Technetium at 0.04 ppm had no effect. However, when seedlings were germinated and allowed to grow for 5 days before Tc was supplied, weight was reduced 36% at 20 ppm Tc, while 5 ppm had no effect.

Gast et al. (1978) examined the effect of Tc as pertechnate ($NH_4TcO_4$) on shoot and root weight of several plants grown from seed for 10 days in nutrient solution containing Tc. Technetium at 0.3 ppm reduced shoot weights of wheat and barley by 22 and 24%, while 0.03 ppm had no effect. A concentration of 1.2 ppm Tc caused decreases of 53% in root and shoot weights of oats, and a 24% reduction in shoot weight of radish, while 0.3 ppm had no effect. Corn shoot weight was reduced 31% by 5.8 ppm Tc, while 3 ppm had no effect. Soybean shoot weight was diminished 50% by 7.8 ppm Tc, while 5.8 ppm had no effect.

Confidence in the 0.2 ppm benchmark for toxicity to plants growing in solution is low because it is based on less than 10 values.

**Mechanism of phytotoxicity**. There are very little data on phytotoxicity of Tc. It is taken up and transported in plants as the pertechnate ion ($TcO_4^-$). The active uptake and toxicity of Tc may be due to its functioning as a nutrient analog, possibly P, S, or Mo (Wildung et al. 1979). The minimal amount of radiation measured in the experimental plants lead researchers to the conclusion that the effects were the result of the element rather than radiation (Wildung et al. 1977).

### 3.1.25 Tellurium

**Experiments conducted in soil.** No information was found on which to base a toxicity benchmark for plants growing in soil.

**Experiments conducted in solution**. Martin (1937b) evaluated the effect of Te (as $K_2TeO_3$) on root and shoot weight, and plant height of wheat seedlings grown in nutrient solution containing Te for 42 days. Tellurium at 2 ppm (lowest concentration tested) reduced root and shoot weights 32 and 35%.

Confidence in the 2 ppm benchmark for toxicity to plants growing in solution is low due to lack of data.

**Mechanism of phytotoxicity**. Very little information on phytotoxicity of Te was found. The biological cycling of the element resembles that of Se although it is not accumulated in plant tissues in concentrations as high as Se (Kabata-Pendias and Pendias 1984). Although plant growth reductions have been measured in plants grown in solution culture to which Te has been added, no information on specific mechanisms of toxicity was found.

### 3.1.26 Thallium

**Experiments conducted in soil**. There are no primary reference data showing toxicity of Tl to plants grown in soil. Confidence in the benchmark is low because it based on a report of unspecified toxic effects on plants grown in a surface soil with the addition of 1 ppm Tl (Kabata-Pendias and Pendias 1984).

Al-attar et al. (1988) investigated the effect of thallium (as nitrate) on the length and weight of the roots and shoots of perennial ryegrass (*Lolium perenne*) seedlings in solution. A concentration of 0.5 ppm of thallium resulted in a 57% reduction in root dry weight, a 59% decrease shoot dry weight, a 26% decrease in root length, and a 54% decrease in shoot length. The NOEC was 0.1 ppm.

**Experiments conducted in solution**. The effect of Tl, as $TlCl_3$, on root elongation of 3-week old Norway spruce seedlings grown for 7 days in nutrient solution (pH 4) was examined by Lamersdorf et al. (1991). The only concentration tested, 0.02 ppm Tl, reduced root elongation by 27%.

The effects of Tl, from $Tl_2SO_4$, on germination and radicle length of radish, cabbage, turnip, lettuce, wheat, and millet after 3 days of growth in solution were determined by Carlson et al. (1991). There was no effect on seed germination up to 40 ppm Tl. Treatment levels were 0, 0.5, 1, 2.5, 5, 7.5, 10, 20, 30, and 40 ppm Tl. A concentration of 0.5 ppm reduced radicle length of lettuce by 65%. A concentration of 1 ppm reduced radicle length of turnip by 63%. Five ppm Tl reduced radicle length of radish by 22%, wheat by 30%, and millet by 35%. Radicle length of millet was reduced 23% by 7.5 ppm Tl.

Carlson et al. (1975) measured 40 and 55% reductions in photosynthesis when corn and sunflower (*Helianthus annuus* L.) seedlings were grown in nutrient solution containing 1 ppm Tl ($TlCl_2$) (lowest concentration tested). Bowen (1979) reports undefined toxic effects on plant growth at this concentration also.

Confidence in the 0.02 ppm benchmark for toxicity to plants growing in solution is moderate.

**Mechanism of phytotoxicity**. Thallium is not essential for plant growth. When soluble forms are available, Tl is readily taken up by plants and translocated to aerial parts, probably because of its similarity to K. Toxic effects on plants include impairment of chlorophyll synthesis and seed germination, reduced transpiration due to interference in stomatal processes, growth reduction, stunting of roots, and leaf chlorosis (Adriano 1986).

### 3.1.27 Tin

**Experiments conducted in soil**. Romney et al. (1975) studied the effect of Sn (as $SnCl_2$) on shoot weight of bush beans grown for 17 days in soil (pH 6). Shoot weight was reduced 22% by 500 ppm Sn, while 50 ppm had no effect.

Kabata-Pendias and Pendias (1984) reported unspecified toxic effects on plants grown in a surface soil with the addition of 50 ppm Sn. Confidence in the benchmark of 50 ppm for Sn is low.

**Experiments conducted in solution.** Romney et al. (1975) studied the effect of Sn (as $SnCl_2$) on shoot weight of bush beans grown for 26 days in nutrient solution. A concentration of 119 ppm reduced shoot weight 81%, while 12 ppm had no effect. Confidence in the benchmark of 100 ppm for Sn in solution is low.

**Mechanism of phytotoxicity.** Tin is not essential to plants although it is readily taken up from nutrient solution. Most remains in the root system (Wallace and Romney 1977b). Tin is an element that is considered relatively innocuous but may be biomethylated to a more toxic form. Although plant growth reductions have been measured in plants grown in solution culture to which Sn has been added, no information on specific mechanisms of toxicity was found.

### 3.1.28 Titanium

**Experiments conducted in soil.** No information was found on which to base a toxicity benchmark for plants growing in soil.

**Experiments conducted in solution.** Wallace et al. (1977a) evaluated the effect of Ti ($TiCl_3$) on root, stem, and leaf weight of bush beans grown in nutrient solution for 21 days. They measured a 23% decrease in leaf weight at 0.069 ppm Ti, the lowest concentration tested.

Hara et al. (1976) measured a 24% reduction in cabbage seedling weight after 55 days of growth in nutrient solution (pH 5) containing 4 ppm Ti ($TiCl_3$). Titanium in solution at 0.4 ppm had no effect.

Confidence in the 0.06 ppm Ti in solution benchmark is low because of lack of data.

**Mechanism of phytotoxicity.** Titanium is not essential for plant growth and when taken up, it remains in the root system (Wallace and Romney 1977b). Toxicity symptoms include chlorosis, necrosis, and stunted growth. No information on specific mechanisms of toxicity was found.

### 3.1.29 Uranium

**Experiments conducted in soil.** Sheppard et al. (1983) grew Swiss chard in a sandy (pH 6.4, CEC 1.2 meq/100 g) and a peaty (pH 3, CEC 65 meq/100 g, % organic matter 92) soil to tested the effects of $^{238}U$ added as uranyl nitrate [$UO_2(NO_3)_2$]. In the sandy soil, root weight was reduced 23% by 5 ppm U (lowest concentration tested), while shoot weight was not effected. In the peaty soil, root weight was reduced 44% by 10 ppm U (lowest concentration tested), while shoot weight was not effected. Confidence in the benchmark of 5 ppm U in soil is low because it is based on this study alone.

**Experiments conducted in solution.** Murthy et al. (1984) examined the effect of U, as $UO_2$, on germination and seedling length of soybean in nutrient solution for 6 days. A concentration of 42 ppm reduced seedling length 33%, while 0.42 ppm had no effect. Seed germination remained unaffected. Confidence in the benchmark of 40 ppm U in solution is low.

**Mechanism of phytotoxicity.** Uranium exists in the water-soluble fraction of plant tissue, probably as the uranyl ion and bound to cell wall proteins (Whitehead et al. 1971). The mechanisms of U phytotoxicity involve inhibition of enzyme systems and possibly binding to nucleic acids (Feldman et al. 1967). The minimal amount of radiation measured in the experimental plants has led researchers to the conclusion that toxic effects are the result of the element rather than radiation (Sheppard et al. 1983).

### 3.1.30 Vanadium

**Experiments conducted in soil.** There are no primary reference data describing toxicity of V to plants grown in soil. Kabata-Pendias and Pendias (1984) report unspecified toxic effects on plants grown in a surface soil with the addition of 50 ppm V. Vanadium added at a concentration of 2.5 ppm was toxic to plants in a study reported by EPA (1980). Confidence in the 2 ppm benchmark for V is low.

**Experiments conducted in solution.** Wallace (1979) examined the effect of V from $NH_4VO_3$ on root and shoot weight of bush bean seedlings grown in nutrient solution (pH 5) for 14 days. Vanadium at 0.51 ppm (lowest concentration tested) reduced root weight 46%. After 55 days, cabbage seedling plant weight was reduced 34% by 4 ppm V added as $VCl_3$ to nutrient solution (pH 5), while 0.4 ppm had no effect on growth (Hara et al. 1976). Plant weight of soybean seedlings grown for 33 days in nutrient solution containing 6 ppm V (as $VOSO_4$) was reduced 36%, while 3 ppm had no effect (Kaplan et al. 1990) on growth.

Nowakowski (1992) determined the effects of V ($NH_4VO_3$) on root and shoot weights of three cultivars of peas when allowed to germinate and grow 14 days in solution containing V. Vanadium at 20 ppm reduced root and shoot weights of the cultivars approximately 40 and 25%.

The effects of V, from $VOSO_4$, on germination and radicle length after 3 days of growth in solution of radish, cabbage, turnip, lettuce, wheat, and millet were determined by Carlson et al. (1991). There was no effect on seed germination up to 40 ppm. Treatment levels were 0, 0.5, 1, 2.5, 5, 7.5, 10, 20, 30, and 40 ppm V for all but millet which was exposed additionally to 50, 60, 70, 80, and 100 ppm V. A concentration of 2.5 ppm reduced radicle length of lettuce by 30%, turnip by 50%, and cabbage by 42%. 10 ppm reduced radicle length of radish by 23%. Wheat was unaffected up to 40 ppm V. Radicle length of millet was reduced 50% by 60 ppm.

Gil et al. (1995) measured 26 and 28% reductions in root fresh weight and shoot dry weight of 2-wk old lettuce seedlings grown in nutrient solution (pH 4.7) containing 0.2 ppm V as $NH_4VO_3$. Vanadium at 0.1 ppm had no effect.

Confidence in the 0.2 ppm V in solution benchmark is low.

**Mechanism of phytotoxicity.** Vanadium is not known to be essential for plant growth although it may be involved in $N_2$ fixation in nodules of legume roots. Toxicity symptoms include chlorosis, dwarfing, and inhibited root growth (Pratt 1966). Vanadium inhibits various enzyme systems while stimulating others, the overall effect on plant growth being negative (Peterson and Girling 1981). After uptake, most vanadium remains in the root system in insoluble form with Ca (Wallace and Romney 1977b).

### 3.1.31 Zinc

**Experiments conducted in soil.** In a pot culture starting with 2-year-old beech trees growing in an organic-rich forest soil (pH 4.8), Hagemeyer et al. (1993) measured a reduction of approximately 40% in annual ring growth in the presence of 3.3 ppm 1M ammonium acetate-extractable Zn when trees were grown for two seasons (lowest concentration tested). Zinc was added as $ZnSO_4$. The results of this study are not directly comparable to others that report the amount of Zn added to the soil; however, the information is presented for reference in order to increase the number of plant types covered.

Muramoto et al. (1990) measured the effects of addition of Zn as ZnO to an alluvial soil (pH 6) on root and stem weights, stem length, and grain yield of wheat and rice grown from seed to maturity. Root weight of rice was reduced about 29% by 1000 ppm (lowest concentration tested). Wheat grain yield and plant weight were reduced 66 and 28% by 1000 ppm (lowest concentration tested).

The number of soybean seeds produced per plant was decreased by 28% when plants were grown in an average garden soil to which 25 ppm Zn was added as $ZnSO_4$ (Aery and Sakar 1991). Zn at 10 ppm had no effect. Nodule weight and number and seed weight were not affected by 25 ppm Zn. Plants were grown from seed to maturity.

White et al. (1979) evaluated the effect of Zn, as $ZnSO_4$, on leaf and root weights of soybeans grown in a sandy loam soil at two pH levels. Leaf weight was reduced 30% by 131 ppm Zn at pH 5.5, while 115 ppm had no effect. At pH 6.5, leaf weight was reduced 33% by 393 ppm Zn.

Lata and Veer (1990) measured reductions in root and shoot lengths and weights of spinach and coriander (*Coriandrum sativum* L.) after 60 days in soil with added Zn form. Total soil Zn concentrations of 87 ppm reduced plant weight of spinach about 45%, and coriander about 22%.

Gall and Barnette (1940) investigated the effect of Zn, as $ZnSO_4$, on corn and cowpeas (*Vigna sinensis* L.) grown in three soils for 30 days from seed. Results of this study are not directly comparable to most others because the authors report effective concentrations as "exchangeable", that is, Zn associated with the colloidal portion of the soil. Corn shoot weight was reduced 68% in a sandy soil at 404 ppm exchangeable Zn, while 202 ppm had no effect. In a sandy loam soil, the reduction was 38% at 334 ppm, while 222 ppm had no effect. In a clay loam soil, the reduction was 33% at 632 ppm, while 474 ppm had no effect. Cowpea shoot weight was reduced 29% in a sandy soil at 141 ppm exchangeable Zn, while 81 ppm had no effect. In a sandy loam soil, the reduction was 46% at 222 ppm, while 112 ppm had no effect. In a clay loam soil, the reduction was 28% at 316 ppm, while 158 ppm had no effect.

Confidence in the 50 ppm benchmark is moderate.

**Experiments conducted in solution.** Carroll and Loneragan (1968) measured effects of Zn on weight of 1-week old seedlings of barrel medic (*Medicago truncatula* L.), subterranean clover (*Trifolium subterraneum* L.), and lucerne (*Medicago sativa* L.) grown for 46 days in nutrient solution (pH 6). Zinc at 0.41 ppm reduced weight 80, 40, and 37%, respectively, while 0.08 ppm had no effect.

Wong and Bradshaw (1982) evaluated the effect of Zn on root and shoot length of rye grass grown in solution (pH 7) with Zn added as $ZnSO_4$. After 14 days, they found a 63% reduction in the length of the longest root in response to 1.85 ppm (lowest concentration tested).

Patel et al. (1976) found a 30% decrease in root and stem weights of chrysanthemum seedlings when grown for 21 days in nutrient solution with 6.5 ppm Zn (as $ZnSO_4$), while 0.65 ppm had no effect.

Wallace et al. (1977b) evaluated the effect of Zn (as $ZnSO_4$) on leaf, stem, and root weights of bush bean seedlings in solution. After 16 days, weights were reduced 34, 41, and 44%, respectively, by 6.6 ppm Zn, while 0.66 ppm had no effect.

Misra et al. (1994) evaluated the effects of several metals on seed germination and root growth of broad bean (Vicia faba). Seed germination was not affected by Zn ($ZnCl_2$) at concentrations up to 10 ppm Zn in nutrient solution. Root elongation of plants exposed for 3 days to 10 ppm. Zn was reduced 30%, while 8 ppm had no effect.

Wang (1994) evaluated the effects of several metals and organic compounds on radicle weight of rice seed germinated and grown for 6 d in solution. The calculated $EC_{50}$ for $ZnCl_2$ was 26 ppm.

The benchmark of 0.4 ppm Zn is based on the work of Carroll and Loneragan (1986). Confidence in the benchmark is low because it is based on less than 10 values from experiments conducted with a limited range of plant species.

**Mechanism of phytotoxicity**. Zinc is an essential element for plant growth. It has a part in many enzymes and is involved in disease protection and metabolism of carbohydrates and proteins. Zinc is actively taken up by roots in ionic form and, to a lesser extent, in organically chelated form (Collins 1981). It is fairly uniformly distributed between roots and shoots being transported in the xylem in ionic form (Wallace and Romney 1977b). Transport in the phloem appears to be as an anionic complex (van Goor and Wiersma 1976). Toxicity symptoms include chlorosis and depressed plant growth (Chapman 1966). It acts to inhibit $CO_2$ fixation, phloem transport of carbohydrates, and alter membrane permeability (Collins 1981).

## 3.2 ORGANIC COMPOUNDS

Numerous organic chemicals exist for which phytotoxicity has not been measured. Feng et al. (1997) and van Gestel et al. (1997) provide Quantitative Structure Activity Relationships (QSAR) for plant growth parameters as affected by substituted anilines and phenols, including chlorinated compounds.

### 3.2.1 Acenaphthene

Hulzebos et al. (1993) evaluated the effects of 75 organic compounds on growth of lettuce from seed for 14 d in two loam soils, and of 1-wk old lettuce seedlings in nutrient solution for 16 to 21 d. The difference in the loams was the clay content (12 and 24%). The calculated $EC_{50}$ value for acenaphthene was 25 ppm in the soil containing 24% clay and >0.1, <0.32 ppm in solution.

**Mechanism of toxicity**. No information was available on the mechanism of toxicity.

### 3.2.2 Aniline

Feng et al. (1996) calculated the EC50 for the effect of several anilines and phenols on the root length of 5-day-old Chinese cabbage plants in solution. The inhibition rate in root elongation versus the log of chemical concentration in solution was plotted. The EC50 reported for aniline was 203.5 ppm.

**Mechanism of toxicity.** No information was available on the mechanism of toxicity.

### 3.2.3 Biphenyl

Hulzebos et al. (1993) evaluated the effects of biphenyl on the growth of lettuce in solution and in a loam soil containing 12% clay, as described for acenaphthene. The calculated $EC_{50}$ value was 68 ppm for the soil and 2.1 ppm in solution.

**Mechanism of toxicity.** No information was available on the mechanism of toxicity.

### 3.2.4 4-Bromoaniline

Feng et al. (1996) calculated the EC50 for the effect of several anilines and phenols on the root length of 5-day-old Chinese cabbage plants in solution. The inhibition rate in root elongation versus the log of chemical concentration in solution was plotted. The EC50 reported for 4-bromoaniline was 37.8 ppm.

**Mechanism of toxicity.** No information was available on the mechanism of toxicity.

### 3.2.5 3-Chloroaniline

Van Gestel et al. (1996) reported the toxicity of four chlorophenols and three chloroanilines on the growth of lettuce (*Latuca sativa*) in a loam soil. The EC50 for a 14-day test using 3-chloroaniline was 23 ppm. The NOEC was approximately a factor of 3.2 lower.

**Mechanism of toxicity.** No information was available on the mechanism of toxicity.

### 3.2.6 4-Chloroaniline

Feng et al. (1996) calculated the EC50 for the effect of several anilines and phenols on the root length of 5-day-old Chinese cabbage plants in solution. The inhibition rate in root elongation versus the log of chemical concentration in solution was plotted. The EC50 reported for 4-chloroaniline was 39.4 ppm.

**Mechanism of toxicity.** No information was available on the mechanism of toxicity.

### 3.2.7 2-Chlorophenol

Feng et al. (1996) calculated the EC50 for the effect of several anilines and phenols on the root length of 5-day-old Chinese cabbage plants in solution. The inhibition rate in root elongation versus the log of chemical concentration in solution was plotted. The EC50 reported for 2-chlorophenol was 58.3 ppm.

**Mechanism of toxicity.** No information was available on the mechanism of toxicity.

### 3.2.8 3-Chlorophenol

Van Gestel et al. (1996) reported the toxicity of four chlorophenols and three chloroanilines on the growth of lettuce (*Latuca sativa*) in a loam soil. The EC50 for a 14-day test using 3-chlorophenol was 7 ppm. The NOEC was approximately a factor of 3.2 lower.

**Mechanism of toxicity.** No information was available on the mechanism of toxicity.

### 3.2.9 4-Chlorophenol

Feng et al. (1996) calculated the EC50 for the effect of several anilines and phenols on the root length of 5-day-old Chinese cabbage plants in solution. The inhibition rate in root elongation versus the log of chemical concentration in solution was plotted. The EC50 reported for 4-chlorophenol was 47.4 ppm.

**Mechanism of toxicity.** No information was available on the mechanism of toxicity.

### 3.2.10 2-Cresol

Feng et al. (1996) calculated the EC50 for the effect of several anilines and phenols on the root length of 5-day-old Chinese cabbage plants in solution. The inhibition rate in root elongation versus the log of chemical concentration in solution was plotted. The EC50 reported for 2-cresol was 54.9 ppm.

**Mechanism of toxicity.** No information was available on the mechanism of toxicity.

### 3.2.11 Di-n-butyl phthalate

Overcash et al. (1982) evaluated the phytotoxicity of di-n-butyl phthalate and toluene on plant growth in two soils. Fescue, corn, and soybeans were grown from seed for 21 days in a clay soil (pH 5, % organic matter 1.6, CEC 8.7 meq/100g soil) and a sandy loam soil (% organic matter approximately 1, CEC approximately 3 meq/100g soil). Both soils were tested at pH 4 and 6. The treatment levels for di-n-butyl phthalate were 200, 2000, or 20000 ppm. In the clay soil, no effect was seen on seed germination at the highest concentration. Corn fresh weight was reduced 23% by 200 ppm. Fescue fresh weight was reduced 73% by 2000 ppm. In the sandy loam soil at pH 4, soybean seed germination was reduced 56% by 200 ppm. Corn fresh weight was reduced 34% by 200 ppm. In the sandy loam soil at pH 6, no effect on seed germination was noted. Fresh weights of corn and soybean were reduced 44 and 29% by 200 ppm. Fescue fresh weight was reduced 56% by 2000 ppm. Confidence in the benchmark of 200 ppm is low.

**Mechanism of toxicity.** Di-n-butyl phthalate has a low vapor pressure and is nonionic. It is biologically and chemically decomposed in soil. Di-n-butyl phthalate may be produced in plants (some phthalate esters are known to be), and it is metabolically degraded by plants and animals (Overcash et al. 1982).

### 3.2.12 3,4-Dichloroaniline

Feng et al. (1996) calculated the EC50 for the effect of several anilines and phenols on the root length of 5-day-old Chinese cabbage plants in solution. The inhibition rate in root elongation versus the log of chemical concentration in solution was plotted. The EC50 reported for 3,4-dichloroaniline was 14.1 ppm.

**Mechanism of toxicity.** No information was available on the mechanism of toxicity.

### 3.2.13 2,4-Dichlorophenol

Feng et al. (1996) calculated the EC50 for the effect of several anilines and phenols on the root length of 5-day-old Chinese cabbage plants in solution. The inhibition rate in root elongation versus the log of chemical concentration in solution was plotted. The EC50 reported for 2,4-dichlorophenol was 17.1 ppm.

**Mechanism of toxicity.** No information was available on the mechanism of toxicity.

### 3.2.14 3,4-Dichlorophenol

Van Gestel et al. (1996) reported the toxicity of four chlorophenols and three chloroanilines on the growth of lettuce (*Latuca sativa*) in a loam soil. The EC50 for a 7-day test using 3,4-dichlorophenol was 25 ppm. The NOEC was approximately a factor of 3.2 lower.

**Mechanism of toxicity.** No information was available on the mechanism of toxicity.

### 3.2.15 Diethylphthalate

Hulzebos et al. (1993) evaluated the effects of diethylphthalate on growth of lettuce in solution in a loam soil containing 12% clay, as described for acenapthene. The calculated $EC_{50}$ value was 134 ppm for the soil and 25 ppm in solution.

**Mechanism of toxicity**. No information was available on the mechanism of toxicity.

### 3.2.16 2,4-Dinitrophenol

Overcash et al. (1982) evaluated the phytotoxicity of 2,4-dinitrophenol on plant growth in two soils as described for di-n-butyl phthalate. Treatment levels were 10, 20, 40, 80, and 100 ppm. In the clay soil, no effect on seed germination was noted. Soybean fresh weight was reduced 63% by 20 ppm. Corn and fescue fresh weights were reduced 35 and 80% by 40 ppm. In the sandy loam soil at pH 4, soybean seed germination was reduced 30%, and fresh weight 65%, by 40 ppm. Corn seed germination was reduced 42% by 80 ppm, while fresh weight was reduced 25% by 20 ppm. Fescue fresh weights were reduced 29% by 40 ppm. In the sandy loam soil at pH 6, no effect on seed germination was noted. Fresh weight of soybean was reduced 23% by 20 ppm, of corn 25% by 40 ppm, and of fescue 24% by 80 ppm. Confidence in the benchmark of 20 ppm is moderate.

**Mechanisms of toxicity**. 2,4-dinitrophenol is more toxic to plants at low pH, where the weak acid is largely in the molecular, undissociated form which is more easily taken up by, and active in, plants than the dissociated anion. Primary modes of action on plants are increasing respiration, uncoupling of oxidative phosphorylation, and activation of ATP-ase. It is relatively persistent in soils, especially at low pH. The pH range of 4 to 6 included in the studies of Overcash et al. (1982) was not great enough to show differences in toxicity due to soil adsorption and differential ionic activity.

### 3.2.17 Furan

Hulzebos et al. (1993) evaluated the effects of furan on growth of lettuce in two soils and solution, as described for acenaphthene. The calculated $EC_{50}$ values for the soil containing 24% clay was >1,000 ppm, and for the soil containing 12% clay it was 617 ppm. The $EC_{50}$ values in solution were 130 and 135 ppm.

### 3.2.18 Heptane

Hulzebos et al. (1993) evaluated the effects of heptane on growth of lettuce in two soils and solution, as described for acenaphthene. The calculated $EC_{50}$ values for both soils was >1000 ppm. The $EC_{50}$ values in solution were 1.7 and 47 ppm.

**Mechanism of toxicity**. No information was available on the mechanism of toxicity.

### 3.2.19 Hexachlorocyclopentadiene

Hulzebos et al. (1993) evaluated the effects of hexachlorocyclopentadiene on growth of lettuce in solution and in a loam soil containing 24% clay, as described for acenaphthene. The calculated $EC_{50}$ value was 10 ppm for the soil and 0.1 ppm in solution.

**Mechanism of toxicity**. No information was available on the mechanism of toxicity.

### 3.2.20 Napthalene

Hulzebos et al. (1993) evaluated the effects of napthalene on growth of lettuce in solution and in loam soil containing 12% clay, as described for acenaphthene. The calculated $EC_{50}$ value was >100 ppm for the soil and 13 ppm in solution.

**Mechanism of toxicity**. No information was available on the mechanism of toxicity.

### 3.2.21 3-Nitroaniline

Feng et al. (1996) calculated the EC50 for the effect of several anilines and phenols on the root length of 5-day-old Chinese cabbage plants in solution. The inhibition rate in root elongation versus the log of chemical concentration in solution was plotted. The EC50 reported for 3-nitroaniline was 69.2 ppm.

### 3.2.22 4-Nitroaniline

Feng et al. (1996) calculated the EC50 for the effect of several anilines and phenols on the root length of 5-day-old Chinese cabbage plants in solution. The inhibition rate in root elongation versus the log of chemical concentration in solution was plotted. The EC50 reported for 4-nitroaniline was 43.6 ppm.

### 3.2.23 Nitrobenzene

McFarlane et al. (1990) examined the effect of nitrobenzene on soybean, barley, lettuce, Russian olive (*Elaeagnus angustifolia* L.), autumn olive, green ash (*Fraxinus pennsylvanica*), hybrid poplar (*Populus* x *robusta*), and honeysuckle grown in nutrient solution. One-year-old autumn olive seedlings exposed for 2 days to 8 ppm nitrobenzene (only concentration tested) experienced reductions of 95 and 90% in photosynthesis and transpiration. Confidence in the solution benchmark is low because it is based on this study alone.

**Mechanism of toxicity**. No information was found on phytotoxicity of nitrobenzene except for the studies showing reduced photosynthesis and transpiration of autumn olive discussed above (McFarlane et al. 1990).

### 3.2.24 4-Nitrophenol

Feng et al. (1996) calculated the EC50 for the effect of several anilines and phenols on the root length of 5-day-old Chinese cabbage plants in solution. The inhibition rate in root elongation versus the log of chemical concentration in solution was plotted. The EC50 reported for 4-nitrophenol was 12.3 ppm.

### 3.2.25 Pentachlorophenol

Hulzebos et al. (1993) evaluated the effects of pentachlorophenol on growth of lettuce in two soils and solution, as described for acenaphthene. Soils with a higher clay content had a higher $EC_{50}$ value for phenol (8 and 3.2 ppm); the $EC_{50}$ value of 0.03 ppm in the solution was lower than in either soil.

Gunther and Pestemer (1990) reported the toxic levels of pentachlorophenol causing reduced fresh weight of shoots of oats (*Avena sativa*) after 14 days of exposure and turnips (*Brassica rapa*) after 10 days of exposure in a sandy loam soil. The EC50s for oats and turnips were 20 and 10 ppm, respectively.

Confidence in the benchmarks for soil and solution, 3 and 0.3 ppm, is low.

**Mechanism of toxicity**. No information was available on the mechanism of toxicity.

### 3.2.26 Phenol

Hulzebos et al. (1993) evaluated the effects of phenol on growth of lettuce in solution and in two soils, as described for acenaphthene. Soils with a higher clay content had a lower $EC_{50}$ value for phenol (79 and 168 ppm); the $EC_{50}$ values in solution were lower (14 and 20 ppm) than in either soil.

Feng et al. (1996) calculated the EC50 for the effect of several anilines and phenols on the root length of 5-day-old Chinese cabbage plants in solution. The inhibition rate in root elongation versus the log of chemical concentration in solution was plotted. The EC50 reported for phenol was 125.6 ppm.

Confidence in the benchmarks for soil and solution, 70 and 10 ppm, is low.

**Mechanism of toxicity**. No information was available on the mechanism of toxicity.

### 3.2.27 Polychlorinated biphenyls (PCBs)

**Aroclor 1254**. Strek and Weber (1980) investigated the effects of the PCB Aroclor 1254 on fescue, sorghum (*Sorghum bicolor* L.), corn, soybean, and beets grown in a sandy soil (pH 4.7, % organic matter 1, CEC 1.5 meq/100g soil) from seed for 16 days. Height, water use, and top fresh weight of corn, sorghum, and fescue were unaffected by the 1000 ppm test concentration. Fresh top weight of three soybean varieties was reduced an average of 28% and water use 43%. Beet height and fresh top weight were reduced 100% and water use 94%. Fresh foliage weight of pigweed (*Amaranthus retroflexus* L.) was assessed in soil containing up to 100 ppm Aroclor 1254. The more sensitive variety had a 22% reduction in weight at 40 ppm, while 20 ppm had no effect.

Strek and Weber (1982b) also evaluated the effect of Aroclor 1254 on pigweed grown in the sandy soil used by Strek and Weber in the 1980 work. They found a 23% reduction in the height of plants grown from seed for 28 days in soil containing 100 ppm. A treatment level of 50 ppm had no effect.

Weber and Mrozek (1979) evaluated the effect of Aroclor 1254 on soybean grown in the sandy soil used by Strek and Weber in the 1980 work. They found a 27% reduction in the fresh shoot weight of plants grown from seed for 26 days in soil containing 100 ppm. A treatment level of 10 ppm had no effect. There was also a 45% reduction in water use at the 100 ppm level.

Confidence in the benchmark of 40 ppm for PCBs is low because it is based on fewer than 10 values.

**Mechanism of toxicity**. Commercial formulations of PCBs are various, usually unquantified, mixes of polychlorinated biphenyls. Although plant growth reductions resulting from PCB addition to soil have been measured, no mechanism of toxicity was suggested. Because cumulative water use seems to be more sensitive to PCBs than plant growth (Weber and Mrozek 1979), it has been suggested that effects on plants may be indirect, following an effect on transpiration (Strek and Weber 1982a). *In vitro* cultures of plant cells are capable of metabolizing and detoxifying PCBs (Fletcher et al. 1987).

### 3.2.28 Styrene

Hulzebos et al. (1993) evaluated the effects of styrene on growth of lettuce in solution and in a loam soil containing 24% clay, as described for acenaphthene. The calculated $EC_{50}$ value was 320 ppm for the soil and 18 ppm in solution.

**Mechanism of toxicity**. No information was available on the mechanism of toxicity.

### 3.2.29 2,3,5,6-Tetrachloroaniline

Van Gestel et al. (1996) reported the toxicity of four chlorophenols and three chloroanilines on the growth of lettuce (*Latuca sativa*) in a loam soil. The EC50 for a 14-day test using 2,3,5,6-tetrachloroaniline was 17 ppm. The NOEC was approximately a factor of 3.2 lower.

**Mechanism of toxicity.** No information was available on the mechanism of toxicity.

### 3.2.30 Tetrachloroethene

Hulzebos et al (1993) evaluated the effects of tetrachloroethene on growth of lettuce in solution and in a loam soil containing 24% clay, as described for acenaphthene. The calculated $EC_{50}$ value was >1,000 ppm for the soil and 12 ppm in solution.

**Mechanism of toxicity**. No information was available on the mechanism of toxicity.

### 3.2.31 Toluene

Overcash et al. (1982) evaluated the phytotoxicity of toluene on plant growth in two soils as described for di-n-butyl phthalate. In the clay soil, no effect on seed germination was noted. Corn fresh weight was reduced 30% by 200 ppm. Soybean fresh weight was reduced 32% by 20,000 ppm. In the sandy loam soil at pH 4, soybean seed germination was reduced 50% by 2000 ppm. Corn seed germination was reduced 86% by 20,000 ppm. In the sandy loam soil at pH 6, no effect on seed germination was noted. Fresh weight of soybean was reduced 40% by 200 ppm, and of corn and fescue, 68 and 22% by 20,000 ppm. Confidence in the benchmark of 200 ppm toluene is low.

Hulzebos et al. (1993) evaluated the effects of toluene on growth of lettuce in solution and in a loam soil containing 12% clay, as described for phenol. The calculated $EC_{50}$ value was >1,000 ppm for the soil and 16 ppm in solution.

**Mechanism of toxicity**. Toluene is a lipophilic compound that is more toxic in vapor form because of its ability to dissolve lipids of cuticle and plasma membranes. It is not actively taken up by plants from soils but may adsorb to root surfaces and enter by dissolving membrane components. Toluene is known to be oxidatively detoxified by plants.

Toluene has been found to negatively affect seed germination and plant weight. Toxic effects appear to be acute because toluene is not accumulated in plants. In the case of seeds, it is thought that high levels of toluene may kill the embryo (Overcash et al. 1982).

### 3.2.32 4-Toluidine

Feng et al. (1996) calculated the EC50 for the effect of several anilines and phenols on the root length of 5-day-old Chinese cabbage plants in solution. The inhibition rate in root elongation versus the log of chemical concentration in solution was plotted. The EC50 reported for 4-toluidine was 102.2 ppm.

**Mechanism of toxicity.** No information was available on the mechanism of toxicity.

### 3.2.33 2,4,5-Trichloroaniline

Van Gestel et al. (1996) reported the toxicity of four chlorophenols and three chloroanilines on the growth of lettuce (*Latuca sativa*) in a loam soil. The EC50 for a 14-day test using 2,4,5-trichloroaniline was 23 ppm. The NOEC was approximately a factor of 3.2 lower.

**Mechanism of toxicity.** No information was available on the mechanism of toxicity.

### 3.2.34 Trichloroethane

Hulzebos et al. (1993) evaluated the effects of trichloroethane on growth of lettuce in solution and in a loam soil containing 24% clay, as described for acenaphthene. The calculated $EC_{50}$ value was >1000 ppm for the soil and 104 ppm in solution.

**Mechanism of toxicity.** No information was available on the mechanism of toxicity.

### 3.2.35 2,4,5-Trichlorophenol

Van Gestel et al. (1996) reported the toxicity of four chlorophenols and three chloroanilines on the growth of lettuce (*Latuca sativa*) in a loam soil. The EC50 for a 14-day test using 2,4,5-trichlorophenol was 4.3 ppm. The NOEC was approximately a factor of 3.2 lower.

**Mechanism of toxicity.** No information was available on the mechanism of toxicity.

### 3.2.36 2,4,6-Trichlorophenol

Feng et al. (1996) calculated the EC50 for the effect of several anilines and phenols on the root length of 5-day-old Chinese cabbage plants in solution. The inhibition rate in root elongation versus the log of chemical concentration in solution was plotted. The EC50 reported for 2,4,6-trichlorophenol was 12.7 ppm.

**Mechanism of toxicity.** No information was available on the mechanism of toxicity.

### 3.2.37 Ortho-xylene

Hulzebos et al. (1993) evaluated the effects of ortho-xylene on growth of lettuce in solution and in loam soil containing 24% clay as described for phenol. The calculated $EC_{50}$ value was >1,000 ppm for the soil and >1, <3.2 ppm in solution.

**Mechanism of toxicity**. No information was available on the mechanism of toxicity.

### 3.2.38 Xylene

Allen et al. (1961) evaluated the effect of xylene in insecticides on emergence of sugar beet seedlings exposed in solution (pH 6) for 2 days. Root length was reduced 32% by 100 ppm xylene, the lowest concentration tested. Confidence in the solution benchmark is low because it is based on this study alone.

**Mechanism of toxicity**. There was no information found on phytotoxicity of xylene except for the study showing reduced beet root growth (Allen et al. 1961).

# 4. RELATIONSHIP BETWEEN SOIL PHYTOTOXICITY BENCHMARKS AND OTHER ECOTOXICOLOGICAL CRITERIA

## 4.1 COMPARISON OF PHYTOTOXICITY BENCHMARKS FOR CONTAMINANTS IN SOIL TO CANADIAN ENVIRONMENTAL QUALITY CRITERIA FOR CONTAMINATED SITES

The Canadian Council of Ministers of the Environment has developed Environmental Quality Criteria for contaminated sites. These are "numerical limits for contaminants in soil and water intended to maintain, improve, or protect environmental quality and human health at contaminated sites in general" (CCME 1991). Remediation criteria are presented for comparison to the phytotoxicity benchmarks because they represent levels considered generally protective of human health and the environment for specified uses of soil (in this case the most conservative use, agriculture, has been chosen) without taking into account site-specific conditions. If contaminant concentrations exceed the remediation criteria for a current or future land use, further investigation or remediation is needed. These criteria have an interim status and their derivation is in the process of refinement. They have been adopted from several Canadian jurisdictions and many lack supporting rationale (CCME, 1991). The remediation criteria are not strictly comparable to our phytotoxicity benchmarks because they also take into account human health and, presumably, soil organisms and the entire food chain dependent upon the soil. New CCME Soil Quality Guidelines are being developed and will be made available in late 1995. The CCME remediation criteria and the soil and solution benchmarks are listed in Table 2.

Contaminant phytotoxicity benchmarks derived by our method are more conservative than those of the CCME except for Be, Cd, F, Sn, Tl, 2,4-dinitrophenol, PCP, and styrene. These differences may be due to the Canadian consideration of a larger number of endpoints or a different level of protection. There is no indication in the source publication as to the level of protection being afforded by the CCME Remediation Criteria; however, if human health is considered in the conservative agriculture land use scenario, one would expect it to be high. This is seen in the case of 2,4-dinitrophenol which has a high mammalian toxicity.

## 4.2 COMPARISON OF PHYTOTOXICITY BENCHMARKS FOR CONTAMINANTS IN SOIL TO RIVM (NETHERLANDS) ECOTOXICOLOGICAL INTERVENTION VALUES FOR CONTAMINANTS IN SOILS

The National Institute of Public Health and Environmental Protection developed Ecotoxicological Intervention Values which represent concentrations of contaminants in soil causing 50% of the species potentially present in an ecosystem to experience adverse effects (van den Berg et al. 1993). They take into account plants, soil fauna, and microorganisms. The method for deriving the values (the RAB method) is described by Denneman and van Gestel in several RIVM publications in Dutch. In order to take the influence of soil characteristics on the bioavailability of compounds, data were corrected for organic matter and clay content as described by van den Berg et al. (1993). Risks resulting from biomagnification were included. The RIVM values and the soil and solution benchmarks are listed in Table 2.

**Table 2. Comparison of screening benchmark concentrations for the phytotoxicity of chemicals in soil to CCME remediation criteria (RC), RIVM ecotoxicological intervention values (EIVs), arithmetic means of elements in uncontaminated soils of the Oak Ridge Reservation (ORR), and geometric means of elements in soils and surficial material of the eastern U.S.**

| Chemical | Screening benchmark (mg/kg) | CCME RC[a] (mg/kg) | RIVM EIVs (mg/kg) | ORR (mg/kg) | USGS eastern U.S. (mg/kg) |
|---|---|---|---|---|---|
| Aluminum | 50 | — | — | 15700 | 33000 |
| Antimony | 5 | 20 | — | 0.46 | 0.52 |
| Arsenic | 10 | 20 | 40 | 9.7 | 4.8 |
| Barium | 500 | 750 | 625 | 87.9 | 290 |
| Beryllium | 10 | 4 | — | 0.77 | 0.55 |
| Boron | 0.5 | 2[b] | — | 10.4 | — |
| Bromine | 10 | — | — | — | 0.62 |
| Cadmium | 4 | 3 | 12 | 0.22 | — |
| Chromium (total) | 1 | 750 | 230 | 24 | 33 |
| Chromium (VI) | — | 8 | — | — | — |
| Cobalt | 20 | 40 | 240 | 15.6 | 5.9 |
| Copper | 100 | 150 | 190 | 11.2 | 13 |
| Fluorine | 200 | 200 | — | — | 130 |
| Iodine | 4 | — | — | — | 0.68 |
| Lead | 50 | 375 | 290 | 26.8 | 14 |
| Lithium | 2 | — | — | 9.4 | 17 |
| Manganese | 500 | — | — | 1318 | 260 |
| Mercury | 0.3[c] | 0.8[d] | 10[d] | 0.20[d] | 0.08[d] |
| Molybdenum | 2 | 5 | <480 | 3.9 | 0.32 |

Table 2 (continued)

| Chemical | Screening benchmark (mg/kg) | CCME RC[a] (mg/kg) | RIVM EIVs (mg/kg) | ORR (mg/kg) | USGS eastern U.S. (mg/kg) |
|---|---|---|---|---|---|
| Nickel | 30 | 150 | 210 | 15.1 | 11 |
| Selenium | 1 | 2 | — | 0.73 | 0.3 |
| Silver | 2 | 20 | — | 1.22 | — |
| Technetium | 0.2 | — | — | — | — |
| Thallium | 1 | 1 | — | 0.50 | — |
| Tin | 50 | 2 | — | — | 0.86 |
| Uranium | 5 | — | — | — | 2.1 |
| Vanadium | 2 | 200 | — | 32.3 | 43 |
| Zinc | 50 | 600 | 720 | 46.2 | 40 |
| 3-Chloroaniline | 20 | | | | |
| 2-Chlorophenol | — | 0.05 | 10 | | |
| 3-Chlorophenol | 7 | 0.05 | 10 | | |
| 4-Chlorophenol | — | 0.05 | 10 | | |
| 2-Cresol | — | 0.1 | 50 | | |
| 2,4-Dichlorophenol | — | 0.05 | 10 | | |
| 3,4-Dichlorophenol | 20 | 0.05 | 10 | | |
| 2,4 Dinitrophenol | 20 | 0.1[e] | — | — | — |
| Di-n-butyl phthalate | 200 | — | — | — | — |
| 4-nitrophenol | — | 0.1 | | | |

Table 2 (continued)

| Chemical | Screening benchmark (mg/kg) | CCME RC[a] (mg/kg) | RIVM EIVs (mg/kg) | ORR (mg/kg) | USGS eastern U.S. (mg/kg) |
|---|---|---|---|---|---|
| Pentachlorophenol | 3 | 0.05[f] | 5 | — | — |
| PCBs | 40 | 0.5 | 70 | — | — |
| Styrene | 300 | 0.10 | — | — | — |
| 2,3,5,6-tetrachloroaniline | 20 | | | | |
| Toluene | 200 | 0.1 | 130 | — | — |
| 2,4,5-Trichloroaniline | 20 | | | | |
| 2,4,5-Trichlorophenol | 4 | 0.05 | 10 | | |
| 2,4,6-Trichlorophenol | — | 0.05 | 10 | | |

[a]Agricultural land-use context.
[b]Hot water soluble B.
[c]Inorganic Hg.
[d]Does not indicate form (organic or inorganic).
[e]Each nonspecified non-chlorinated phenolic compound is not to exceed 0.1 ppm.
[f]Each nonspecific chlorinated phenolic compound is not to exceed 0.05 ppm.

# 5. COMPARISON OF PHYTOTOXICITY BENCHMARKS FOR CONTAMINANTS IN SOIL TO CONCENTRATIONS OF CHEMICALS IN UNPOLLUTED SOILS

## 5.1 COMPARISON TO USGS ELEMENT CONCENTRATIONS IN SOILS AND OTHER SURFICIAL MATERIALS OF THE EASTERN UNITED STATES

To place the three sets of critical values into a broader perspective, soil chemical concentrations are presented as reported by the U.S. Geological Survey (USGS) in a survey of soils of the eastern United States (Shacklette and Boerngen 1984) (Table 2). These samples were collected and analyzed by the USGS to represent, as far as possible, soils that were very little altered from their natural condition and that supported native plants. The values are presented as "total" concentrations.

It is interesting to compare the levels of elements cited in the literature as toxic against concentrations of those same elements found in natural (i.e., not directly contaminated) soils. This comparison is reasonable in most cases because benchmarks were generally based on nominal soil concentrations (i.e., those added to the soil by the experimenter) as opposed to a measure of either total concentration or of the plant-available quantity of the element in the soil. Seldom was the background level of the "contaminant" element in the soil measured, the assumption being that there is very little of the element existing naturally in the soil compared to treatment levels added. This is often, but not always, a reasonable assumption. The USGS compilation contains concentrations of elements mainly derived from strong acid extractions, although, in the case of uranium, neutron activation was used to measure a true total concentration. Soils of the eastern United States were chosen for comparison because most of the experimental results used to develop the benchmarks were derived from agricultural soils of the eastern United States. Surficial deposits of the western United States, especially arid and mountainous regions, may contain unusually high concentrations of naturally-occurring trace elements.

For several of the metals, the phytotoxicity benchmark was below the geometric mean for the element in soils and surficial deposits in the eastern United States. Comparing the benchmarks to the acid-extractable element data, a large discrepancy is realized between the USGS soil Al value and the low soil benchmark based on a quantity of Al added to soil. Al is present in most soils in exchangeable and amorphous forms that are not readily available to plants. The acid extraction removes for measurement all exchangeable and some portion of the amorphous Al. In the case of Cr, Li, and V, the form of the element added or some other aspect of the experimental design may account for the low benchmark concentration as compared to mean levels in soils.

## 5.2 COMPARISON TO DOE OAK RIDGE RESERVATION BACKGROUND SOIL CHARACTERIZATION ELEMENT CONCENTRATIONS IN SOILS

The Background Soil Characterization Project at the Oak Ridge Reservation was established to determine the background concentrations of organics, metals, and radionuclides in natural soils that are important to environmental restoration projects (Watkins et al. 1993). Soils were sampled, field classified, and analyzed for chemicals using several methods. The data presented in Table 2 are arithmetic means of 46 sampling sites of elements extracted using nitric acid and hydrogen peroxide (EPA 1986). This standard EPA acid digestion for sediments, sludges, and soils is not explicitly meant to extract total elements from a sample. A comparison with total soil concentrations of elements measured by neutron activation analysis shows that for many elements (Sb, As, Cr, Co, Mn, Si, V, Zn) the acids used do extract most of the element in question (Watkins et al. 1993). Unfortunately, not all elements are amenable to measurement by neutron activation analysis.

As with the USGS data, there is a large discrepancy between the Background Soil Characterization Project soil Al value and the soil phytotoxicity benchmark based on a quantity of Al added to soil. The high manganese levels of geologic origin at the Oak Ridge Reservation emphasize the need for local reference soils for comparison to waste site soils. In the case of Cr, Li, and V, the form of the element added or some other aspect of the experimental design may account for the low benchmark concentrations as compared to levels found in Oak Ridge Reservation soils.

# 6. RECOMMENDATIONS AND CONCLUSIONS

The values presented in Table 1 are intended for contaminant screening in the hazard identification (problem formulation) phase of ecological risk assessments. Chemicals with soil concentrations that exceed both the phytotoxicity benchmark for soil and the background soil concentration for the soil type, and which may be derived from waste disposal, are contaminants of potential concern. Background soil concentrations have been derived for the Oak Ridge Reservation and should be generated for other Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) sites as well. Similarly, soil solution or shallow groundwater concentrations that exceed both the phytotoxicity benchmark for solutions and the background water concentration for the aquifer, which may be derived from waste disposal, and to which plant roots may be exposed are contaminants of potential concern.

For baseline ecological risk assessments, and other assessments that may lead to regulatory actions, assessors should consult the primary sources of toxicity data and then determine the applicability of the data to their specific site. In addition, assessments should not blindly rely on laboratory toxicity data. Where phytotoxicity is suspected, phytotoxicity tests should be performed with the contaminated soil. In addition, the site should be surveyed for signs of phytotoxicity such as inexplicable bare areas, low plant diversity, low plant vigor, or symptoms of toxic injury.

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# APPENDIX A

# PHYTOTOXICITY DATA DERIVED FROM EXPERIMENTS CONDUCTED IN SOIL

**Table A.1. Phytotoxicity data derived from experiments conducted in soil**
[All chemical concentrations in soils and plants are mg of the element/kg medium; OM = % organic matter in the soil; CEC = cation exchange capacity in milliequivalents/100 g soil (dry weight)]

| Chemical | Chemical form | Soil type | CEC | % OM | pH | Plant species | DUR (D) | Soil NOEC | Soil LOEC | Growth parameter | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Aluminum | Al2(SO4)3 | silt loam | | | 5 | white clover | | | 50 | seedling establish | Mackay et al. 1990 |
| Antimony | | surface soil | | | | | | | 5 | phytotoxic | Kabata-Pendias & Pendias 1984 |
| Arsenic | $NaAsO_2$ | sand | | 1 | 6 | barley | 365 | | 2 | grain yield | Jiang & Singh 1994 |
| Arsenic | As2O3 | sandy loam | | | | cotton | 42 | | 11.2 | shoot weight | Deuel & Swoboda 1972 |
| Arsenic | As2O3 | sandy loam | | | | soybean | 42 | | 11.2 | shoot weight | Deuel & Swoboda 1972 |
| Arsenic | As2O3 | black clay | | | | soybean | 42 | | 22.4 | shoot weight | Deuel & Swoboda 1972 |
| Arsenic | $NaAsO_2$ | loam | | 6 | 5 | barley | 365 | 10 | 50 | grain yield | Jiang & Singh 1994 |
| Arsenic | $NaAsO_2$ | sand | | 1 | 6 | ryegrass | 365 | 10 | 50 | grain yield | Jiang & Singh 1994 |
| Arsenic | $NaHAsO_4$ | sand | | 1 | 6 | barley | 365 | 10 | 50 | grain yield | Jiang & Singh 1994 |
| Arsenic | As2O3 | black clay | | | | cotton | 42 | 67.2 | 89.6 | shoot weight | Deuel & Swoboda 1972 |

Table A.1 (continued)

| Chemical | Chemical form | Soil type | CEC | % OM | pH | Plant species | DUR (D) | Soil NOEC | Soil LOEC | Growth parameter | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Arsenic | NaH2AsO4 | sandy loam | | | 7 | corn | 28 | 10 | 100 | fresh weight | Woolson et al. 1971 |
| Arsenic | Al(H2AsO4)3 | loamy sand | | | 7 | corn | 28 | 10 | 100 | fresh weight | Woolson et al. 1971 |
| Arsenic | Ca(H2AsO4)2 | loamy sand | | | 7 | corn | 28 | 10 | 100 | fresh weight | Woolson et al. 1971 |
| Arsenic | $NaAsO_2$ | loam | | 6 | 5 | ryegrass | 365 | 50 | 250 | grain yield | Jiang & Singh 1994 |
| Arsenic | $Na_2HAsO_4$ | loam | | 6 | 5 | ryegrass | 365 | 50 | 250 | grain yield | Jiang & Singh 1994 |
| Arsenic | $Na_2HAsO_4$ | sand | | 1 | 6 | ryegrass | 365 | 50 | 250 | grain yield | Jiang & Singh 1994 |
| Arsenic | $Na_2HAsO_4$ | loam | | 6 | 5 | barley | 365 | 50 | 250 | grain yield | Jiang & Singh 1994 |
| Arsenic | As2O3 | | | | | spruce | 335 | | 1000 | height | Rosehart & Lee 1973 |
| Barium | Ba(NO3)2 | loam | | | | barley | 14 | | 500 | plant weight | Chaudhry et al. 1977 |
| Barium | Ba(NO3)2 | loam | | | | bush beans | 14 | 1000 | 2000 | plant weight | Chaudhry et al. 1977 |
| Beryllium | | surface soil | | | | | | | 10 | phytotoxic | Kabata-Pendias & Pendias 1984 |

Table A.1 (continued)

| Chemical | Chemical form | Soil type | CEC | % OM | pH | Plant species | DUR (D) | Soil NOEC | Soil LOEC | Growth parameter | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Beryllium | $BeSO_4$ | sand | | | 4.9 | soybean | 14 | | 25LCT | shoot weight | Sajwan et al. 1996 |
| Beryllium | $BeSO_4$ | loamy sand | | | 5.5 | soybean | 14 | | 25LCT | shoot weight | Sajwan et al. 1996 |
| Boron | H3BO3 | silt loam | 23 | 6 | 6 | corn | 49 | | 0.5 | shoot weight | John et al. 1977 |
| Boron | H3BO3 | muck | 117 | 56 | 5 | corn | 49 | 10 | 50 | shoot weight | John et al. 1977 |
| Boron | H3BO3 | silt loam | 16 | 3 | 6 | corn | 49 | 10 | 50 | shoot weight | John et al. 1977 |
| Bromine | | surface soil | | | | | | | 10 | phytotoxic | Kabata-Pendias & Pendias 1984 |
| Cadmium | CdCl2 | silt loam | 8 | | 6 | soybean | 28 | | 1 | shoot weight | Miller et al. 1976 |
| Cadmium | CdCl2 | sand + peat | | | 6 | soybeans | 42 | | 1.25 | plant weight | Strickland et al. 1979 |
| Cadmium | CdCl2 | soil + sand | | | | spruce | 98 | 1 | 2 | root & shoot weights | Burton et al. 1984 |
| Cadmium | CdCl2 | sand + peat | 0.4 | 0.5 | 6 | soybeans | 42 | 1.25 | 2.5 | plant weight | Strickland et al. 1979 |
| Cadmium | CdCl2 | silty clay loam | 31 | 4 | 7 | radish | 26 | | 2.5 | root weight | Haghiri 1973 |
| Cadmium | CdCl2 | silty clay loam | 31 | 4 | 7 | lettuce | 37 | | 2.5 | plant weight | Haghiri 1973 |
| Cadmium | | loamy sand | 2 | | 6 | corn | 28 | | 2.5 | shoot weight | Miller et al. 1977 |
| Cadmium | | loamy sand | | 1 | 8 | spinach | | 2 | 4 | plant weight | Sadana & Singh 1987b |

Table A.1 (continued)

| Chemical | Chemical form | Soil type | CEC | % OM | pH | Plant species | DUR (D) | Soil NOEC | Soil LOEC | Growth parameter | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Cadmium | CdSO4 | silt loam | 14 | | 8 | spinach | | | 4 | leaf weight | Bingham et al. 1975 |
| Cadmium | CdSO4 | silt loam | 14 | | 8 | soybean | | | 5 | bean weight | Bingham et al. 1975 |
| Cadmium | CdCl2 | silty clay loam | | | | sycamore | 90 | | 5 | leaf weight | Carlson & Bazzaz 1977 |
| Cadmium | CdCl2 | silty clay loam | 31 | 4 | 7 | wheat | 35 | 2.5 | 5 | shoot weight | Haghiri 1973 |
| Cadmium | Cd(NO3)2 | sand:peat:soil | | | 5 | beech | | | | annual ring width | Hagemeyer et al. 1993 |
| Cadmium | CdSO4 | silt loam | 14 | | 8 | curley cress | | | 8 | leaf weight | Bingham et al. 1975 |
| Cadmium | CdCl2 | sand | 6 | 2 | 5 | black-eyed susan | 42 | | 10 | germination; root&shoot weights | Miles & Parker 1979a |
| Cadmium | CdCl2 | sand | 6 | 2 | 5 | blazing star | 42 | | 10 | root & shoot weights | Miles & Parker 1979a |
| Cadmium | CdCl2 | sand | 6 | 2 | 5 | thimbleweed | 42 | | 10 | shoot weight | Miles & Parker 1979a |
| Cadmium | CdCl2 | sand | 6 | 2 | 5 | bergamot | 42 | | 10 | root weight | Miles & Parker 1979a |
| Cadmium | CdCl2 | silt loam | 7 | | 5 | soybean | 28 | 1 | 10 | shoot weight | Miller et al. 1976 |
| Cadmium | CdCl2 | silt loam | 9 | | 6 | soybean | 28 | 1 | 10 | shoot weight | Miller et al. 1976 |

Table A.1 (continued)

| Chemical | Chemical form | Soil type | CEC | % OM | pH | Plant species | DUR (D) | Soil NOEC | Soil LOEC | Growth parameter | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Cadmium | CdCl2 | silt loam | 7 | | 7 | soybean | 28 | 1 | 10 | shoot weight | Miller et al. 1976 |
| Cadmium | CdCl2 | loamy sand | 2 | | 6 | soybean | 28 | 1 | 10 | shoot weight | Miller et al. 1976 |
| Cadmium | CdCl2 | Brown earth | | | 5 | radish | 42 | | 10 | root & shoot weights | Khan & Frankland 1983 |
| Cadmium | CdCl2 | Brown earth | | | 5 | oats | 42 | | 10 | root weight | Khan & Frankland 1984 |
| Cadmium | | loamy sand | | 0.9 | 8 | wheat | | | 10 | grain yield | Sadana & Singh 1987a |
| Cadmium | CdCl2 | sand | 12 | 2.5 | 8 | bluestem | 84 | | 10 | root & shoot weights | Miles & Parker 1979b |
| Cadmium | CdCl2 | silty clay loam | 31 | 4 | 7 | soybean | 35 | 5 | 10 | shoot weight | Haghiri 1973 |
| Cadmium | CdCl2 | surface soil | | | | soybean | | 5 | 10 | seeds/plant | Aery & Sakar 1991 |
| Cadmium | CdCl2 | sand + peat | 1 | 1 | 6 | soybeans | 42 | 5 | 10 | plant weight | Strickland et al. 1979 |
| Cadmium | CdSO4 | silt loam | 14 | | 8 | lettuce | | | 13 | head weight | Bingham et al. 1975 |
| Cadmium | C4H6CdO4 | acid Cambisol | | 1.7 | 6 | wheat | 28 | 7 | 14.1 | shoot weight | Reber 1989 |
| Cadmium | CdCl2 | humic sand | | 3.7 | 5 | tomato | 14 | 3.2 | 16 | fresh shoot weight | Adema & Henzen 1989 |
| Cadmium | CdSO4 | silt loam | 14 | | 8 | corn | | | 18 | grain yield | Bingham et al. 1975 |

Table A.1 (continued)

| Chemical | Chemical form | Soil type | CEC | % OM | pH | Plant species | DUR (D) | Soil NOEC | Soil LOEC | Growth parameter | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Cadmium | CdSO4 | silt loam | 14 | | 8 | carrot | | | 20 | tuber weight | Bingham et al. 1975 |
| Cadmium | CdCl2 | sandy loam | | 1.5 | 6 | red oak | 112 | 10 | 20 | plant weight | Dixon 1988 |
| Cadmium | CdCl2 | sandy+clay loam | 15 | 1 | 8 | wheat | | 10 | 20 | grain & straw yields | Singh et al. 1991 |
| Cadmium | CdCl2 | sand + peat | 1.5 | 2 | 6 | soybeans | 42 | 10 | 20 | plant weight | Strickland et al. 1979 |
| Cadmium | CdCl2 | loamy sand | 2 | 2.1 | 7 | corn | 7 | 15 | 25 | root length | Hassett et al. 1976 |
| Cadmium | CdCl2 | sand | 6 | 2.2 | 5 | corn | 35 | | 28 | plant weight | Traynor & Knezek 1973 |
| Cadmium | CdSO4 | silt loam | 14 | | 8 | turnip | | | 28 | tuber weight | Bingham et al. 1975 |
| Cadmium | CdCl2 | sand | 6 | 2 | 5 | Ky bluegrass | 42 | 10 | 30 | root & shoot weights | Miles & Parker 1979a |
| Cadmium | CdCl2 | sand | 6 | 2 | 5 | bluestem | 42 | 10 | 30 | root & shoot weights | Miles & Parker 1979a |
| Cadmium | CdCl2 | sand | 6 | 2 | 5 | poison-ivy | 42 | 10 | 30 | root & shoot weights | Miles & Parker 1979a |
| Cadmium | CdO | alluvial | | | 6 | wheat | | 10 | 30 | grain yield | Muramoto et al. 1990 |
| Cadmium | CdCl2 | loam | | 1.4 | 8 | lettuce | 14 | 3.2 | 33 | fresh shoot weight | Adema & Henzen 1989 |

Table A.1 (continued)

| Chemical | Chemical form | Soil type | CEC | % OM | pH | Plant species | DUR (D) | Soil NOEC | Soil LOEC | Growth parameter | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Cadmium | CdCl2 | silt loam | 38 | 11.8 | 5 | spinach | | | 40 | root & leaf weights | John 1973 |
| Cadmium | CdCl2 | silt loam | 38 | 11.8 | 5 | peas | | | 40 | seed, pod, vine weights | John 1973 |
| Cadmium | CdCl2 | silt loam | 38 | 11.8 | 5 | oats | | | 40 | grain yield | John 1973 |
| Cadmium | CdCl2 | silt loam | 38 | 11.8 | 5 | radish | | | 40 | tuber & top weights | John 1973 |
| Cadmium | CdSO4 | silt loam | 14 | | 8 | field bean | | | 40 | bean weight | Bingham et al. 1975 |
| Cadmium | CdCl2 | Brown earth | | | 5 | wheat | 42 | | 50 | root weight | Khan & Frankland 1984 |
| Cadmium | CdSO4 | silt loam | 14 | | 8 | wheat | | | 50 | grain yield | Bingham et al. 1975 |
| Cadmium | CdCl2+CdO | Brown earth | | | 5 | radish | 42 | | 50 | root weight | Khan & Frankland 1984 |
| Cadmium | CdSO4 | silt loam | 14 | | 8 | radish | | | 96 | tuber weight | Bingham et al. 1975 |
| Cadmium | CdCl2 | humic sand | | 3.7 | 5 | oats | 14 | 10 | 97 | fresh shoot weight | Adema & Henzen 1989 |
| Cadmium | CdCl2 | silt loam | 21 | | 6 | rye | | 50 | 100 | shoot weight | Carlson & Rolfe 1979 |
| Cadmium | CdCl2 | surface soils | 38 | 12.9 | 6 | radish | 21 | | 100 | top & root weights | John et al. 1972b |

Table A.1 (continued)

| Chemical | Chemical form | Soil type | CEC | % OM | pH | Plant species | DUR (D) | Soil NOEC | Soil LOEC | Growth parameter | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Cadmium | CdO | alluvial | | | 6 | rice | | 30 | 100 | root & shoot weights | Muramoto et al. 1990 |
| Cadmium | CdO | Brown earth | | | 5 | wheat | 42 | | 100 | root weight | Khan & Frankland 1984 |
| Cadmium | CdO | Brown earth | | | 5 | radish | 42 | | 100 | root & shoot weights | Khan & Frankland 1983 |
| Cadmium | CdCl2 | silt loam | 16 | | 7 | soybean | 28 | 10 | 100 | shoot weight | Miller et al. 1976 |
| Cadmium | C4H6CdO4 | Phaeosem | | 2.2 | 7 | wheat | 28 | 56.3 | 113 | shoot weight | Reber 1989 |
| Cadmium | CdCl2 | humic sand | | 3.7 | 5 | lettuce | 14 | 32 | 136 | fresh shoot weight | Adema & Henzen 1989 |
| Cadmium | CdCl2 | loam | | 1.4 | 8 | oats | 14 | 10 | 159 | leaf weight | Adema & Henzen 1989 |
| Cadmium | CdSO4 | silt loam | 14 | | 8 | tomato | | | 160 | fruit weight | Bingham et al. 1975 |
| Cadmium | CdSO4 | silt loam | 14 | | 8 | zucchini | | | 160 | fruit weight | Bingham et al. 1975 |
| Cadmium | CdSO4 | silt loam | 14 | | 8 | cabbage | | | 170 | head weight | Bingham et al. 1975 |
| Cadmium | CdCl2 | loam | | 1.4 | 8 | tomato | 14 | 32 | 171 | fresh shoot weight | Adema & Henzen 1989 |
| Cadmium | CdCl2 | silt loam | 38 | 11.8 | 5 | lettuce | | 40 | 200 | root & leaf weights | John 1973 |

**Table A.1 (continued)**

| Chemical | Chemical form | Soil type | CEC | % OM | pH | Plant species | DUR (D) | Soil NOEC | Soil LOEC | Growth parameter | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Cadmium | CdCl2 | silt loam | 38 | 11.8 | 5 | broccoli | | 40 | 200 | leaf weight | John 1973 |
| Cadmium | CdCl2 | silt loam | 38 | 11.8 | 5 | cauliflower | | 40 | 200 | root & leaf weights | John 1973 |
| Cadmium | CdCl2 | silt loam | 38 | 11.8 | 5 | carrot | | 40 | 200 | root, tuber,top weight | John 1973 |
| Cadmium | | loam | | | 7 | cotton | 35 | | 300 | leaf & stem weights | Rehab & Wallace 1978 |
| Cadmium | | loam | | | 7 | cotton | 35 | | 300 | leaf & stem weights | Rehab & Wallace 1978 |
| Chromium | K2Cr2O7 | loam | | 1.4 | 8 | lettuce | 14 | 0.35 | 1.8 | fresh shoot weight | Adema & Henzen 1989 |
| Chromium | K2Cr2O7 | loam | | 1.4 | 8 | tomato | 14 | 3.2 | 6.8 | fresh shoot weight | Adema & Henzen 1989 |
| Chromium | K2Cr2O7 | loam | | 1.4 | 8 | oats | 14 | 3.5 | 7.4 | fresh shoot weight | Adema & Henzen 1989 |
| Chromium | K2Cr2O7 | humic sand | | 3.7 | 5 | lettuce | 14 | | >11 | fresh shoot weight | Adema & Henzen 1989 |
| Chromium | K2Cr2O7 | humic sand | | 3.7 | 5 | tomato | 14 | 10 | 21 | fresh shoot weight | Adema & Henzen 1989 |
| Chromium | K2Cr2O7 | loam | | | | soybean | 3 | 10 | 30 | fresh shoot weight | Turner & Rust 1971 |
| Chromium | K2Cr2O7 | humic sand | | 3.7 | 5 | oats | 14 | 11 | 31 | fresh shoot weight | Adema & Henzen 1989 |

Table A.1 (continued)

| Chemical | Chemical form | Soil type | CEC | % OM | pH | Plant species | DUR (D) | Soil NOEC | Soil LOEC | Growth parameter | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Cobalt | | surface soil | | | | | | | 25 | phytotoxic | Kabata-Pendias & Pendias 1984 |
| Copper | CuSO4 | sand | 12 | 2.5 | 8 | bluestem | 84 | | 100 | root & shoot weights | Miles & Parker 1979b |
| Copper | CuSO4 | sand | 6 | 1.9 | 5 | bluestem | 84 | | 100 | root & shoot weights | Miles & Parker 1979b |
| Copper | CuSO4 | loam | | | | bush beans | 17 | 100 | 200 | leaf weight | Wallace et al. 1977b |
| Fluorine | | surface soil | | | | | | | 200 | phytotoxic | Kabata-Pendias & Pendias 1984 |
| Iodine | KI | loam | | | 7 | tomato | 97 | 0.4 | 4 | top weight | Newton & Toth 1952 |
| Iodine | KI | sand | | | 7 | tomato | 97 | 0.4 | 4 | top weight | Newton & Toth 1952 |
| Iodine | KI | silt loam | | | 7 | tomato | 97 | 0.4 | 4 | top weight | Newton & Toth 1952 |
| Iodine | KI | silt loam | | | 7 | tomato | 97 | 0.4 | 4 | top weight | Newton & Toth 1952 |
| Lead | PbCl2 | silty clay loam | | | | sycamore | 90 | | 50 | leaf weight | Carlson & Bazzaz 1977 |
| Lead | PbCl2 | sandy loam | | 1.5 | 6 | red oak | 112 | 20 | 50 | plant weight | Dixon 1988 |
| Lead | PbCl2 | soil + sand | | 45.3 | 3 | spruce | 98 | 50 | 100 | root & shoot weights | Burton et al. 1984 |

**Table A.1 (continued)**

| Chemical | Chemical form | Soil type | CEC | % OM | pH | Plant species | DUR (D) | Soil NOEC | Soil LOEC | Growth parameter | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Lead | PbCl2 | soil:sand:peat | | | | autumn olive | 49 | 80 | 160 | transpiration | Rolfe & Bazzaz 1975 |
| Lead | | loamy sand | 2 | | 6 | corn | 31 | 125 | 250 | plant weight | Miller et al. 1977 |
| Lead | PbCl2 | sand | 12 | 2.5 | 8 | bluestem | 84 | | 450 | root & shoot weights | Miles & Parker 1979b |
| Lead | PbCl2 | sand | 6 | 1.93 | 5 | bluestem | 84 | | 450 | root weight | Miles & Parker 1979b |
| Lead | PbCl2 | Brown earth | | | 5 | oat | 42 | 100 | 500 | root weight | Khan & Frankland 1984 |
| Lead | PbCl2 | loamy sand | 2 | 2.1 | 7 | corn | 7 | 250 | 500 | root length | Hassett et al. 1976 |
| Lead | PbCl2 | Brown earth | | | 5 | radish | 42 | 100 | 500 | root weight | Khan & Frankland 1983 |
| Lead | PbCl2 | silty clay loam | 46 | 17 | 4 | lettuce | 30 | | 1000 | leaf weight | John & van Laerhoven 1972 |
| Lead | Pb(NO3)2 | silty clay loam | 46 | 17 | 4 | lettuce | 30 | | 1000 | leaf weight | John & van Laerhoven 1972 |
| Lead | PbCl2 | Brown earth | | | 5 | wheat | 42 | 500 | 1000 | root weight | Khan & Frankland 1984 |
| Lead | PbO | alluvial | | | 6 | wheat | | 300 | 1000 | root & shoot weights | Muramoto et al. 1990 |
| Lead | PbO | Brown earth | | | 5 | radish | 42 | | 1000 | root weight | Khan & Frankland 1983 |

Table A.1 (continued)

| Chemical | Chemical form | Soil type | CEC | % OM | pH | Plant species | DUR (D) | Soil NOEC | Soil LOEC | Growth parameter | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Lead | PbCl2 | silt loam | 21 | | 6 | rye | | 1000 | 5000 | shoot weight | Carlson & Rolfe 1979 |
| Lead | PbCl2 | silt loam | 21 | | 6 | fescue | | 1000 | 5000 | shoot weight | Carlson & Rolfe 1979 |
| Lithium | LiSO4 | surface soil | | | | orange | 180 | | 2 | phytotoxic | Aldrich et al. 1971 |
| Lithium | LiCl | loam | | | 6 | bush beans | 10 | 10 | 25 | leaf weight | Wallace et al. 1977c |
| Lithium | LiNO3 | loam | | | 6 | cotton | 16 | 25 | 50 | leaf & stem weights | Wallace et al. 1977c |
| Lithium | Li2C2O4 | loam | | | 6 | barley | 10 | | 500 | shoot weight | Wallace. 1979 |
| Manganese | MnSO4 | loam | | | | bush beans | 17 | | 500 | stem weight | Wallace et al. 1977b |
| Mercury | | surface soil | | | | | | | 0.3 | phytotoxic | Kabata-Pendias & Pendias 1984 |
| Mercury | chloralkali waste | clayey sand | | 0.7 | 7.4 | barley | 7 | 34.9 | 64.0 | Seedling height | Panda et al. 1992 |
| Molydbenum | | | | | | | | | 2 | phytotoxic | Kabata-Pendias & Pendias 1984 |
| Nickel | NiSO4 | loam | | | 6 | barley | 14 | | 25 | shoot weight | Wallace et al. 1977d |
| Nickel | NiCl2 | sandy loam | | 1.5 | 6 | red oak | 112 | 20 | 50 | plant weight | Dixon 1988 |

Table A.1 (continued)

| Chemical | Chemical form | Soil type | CEC | % OM | pH | Plant species | DUR (D) | Soil NOEC | Soil LOEC | Growth parameter | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Nickel | NiCl2 | | 6 | 1.4 | 6 | oats | 110 | 20 | 50 | grain & straw weights | Halstead et al. 1969 |
| Nickel | NiSO4 | loam | | | 6 | bush beans | 14 | 25 | 100 | leaf weight | Wallace et al. 1977d |
| Nickel | NiSO4 | loam | | | 6 | bush beans | 14 | | 100 | shoot weight | Wallace et al. 1977d |
| Nickel | | loam | | | 7 | cotton | 35 | | 100 | leaf & stem weights | Rehab & Wallace 1978 |
| Nickel | | loam | | | 7 | cotton | 35 | | 100 | leaf & stem weights | Rehab & Wallace 1978 |
| Nickel | NiCl2 | | 12 | 4.1 | 6 | oats | 110 | 50 | 100 | straw weight | Halstead et al. 1969 |
| Nickel | NiSO4 | loam | | | 5 | ryegrass | 28 | 90 | 180 | shoot weight | Khalid & Tinsley 1980 |
| Nickel | NiSO4 | loam | | | 4 | corn | 14 | 100 | 250 | shoot weight | Wallace et al. 1977d |
| Nickel | NiSO4 | loam | | | 8 | bush beans | 14 | 100 | 250 | shoot weight | Wallace et al. 1977d |
| Nickel | NiSO4 | loam | | | 6 | corn | 14 | 100 | 250 | shoot weight | Wallace et al. 1977d |
| Nickel | NiSO4 | loam | | | 8 | corn | 14 | 100 | 250 | shoot weight | Wallace et al. 1977d |

Table A.1 (continued)

| Chemical | Chemical form | Soil type | CEC | % OM | pH | Plant species | DUR (D) | Soil NOEC | Soil LOEC | Growth parameter | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Nickel | NiCl2 | sand | 5.7 | 2.2 | 5 | corn | 35 | 220 | 294 | plant weight | Traynor & Knezek 1973 |
| Selenium | Na2SeO4 | loamy sand | 4 | 18.5 | 6 | sorgrass | 42 | | 1 | shoot weight | Carlson et al. 1991 |
| Selenium | Na2SeO4 | sand | 3 | 11 | 5 | sorgrass | 42 | | 1 | shoot weight | Carlson et al. 1991 |
| Selenium | Na2SeO4 | loamy sand | 4 | 18.5 | 6 | sorgrass | 42 | | 1 | shoot weight | Carlson et al. 1991 |
| Selenium | Na2SeO4 | sand | 3 | 11 | 7 | sorgrass | 42 | | 1 | shoot weight | Carlson et al. 1991 |
| Selenium | Na2SeO4 | sandy loam | | 13 | 7 | alfalfa | | 0.5 | 1.5 | shoot weight | Wan et al. 1988 |
| Selenium | Na2SeO4 | clay loam | | 15 | 6 | alfalfa | | 0.5 | 1.5 | shoot weight | Wan et al. 1988 |
| Selenium | Na2SeO4 | clay loam | | 13 | 7 | alfalfa | | 0.5 | 1.5 | shoot weight | Wan et al. 1988 |
| Selenium | Na2SeO3 | sand | 3 | 11 | 5 | sorgrass | 42 | 1 | 2 | shoot weight | Carlson et al. 1991 |
| Selenium | Na2SeO4 | silty clay loam | | 6.5 | 7 | alfalfa | | 1 | 2 | shoot weight | Soltanpour & Workman 1980 |
| Selenium | Na2SeO4 | silty clay loam | | 5 | 8 | alfalfa | | 1 | 2 | shoot weight | Soltanpour & Workman 1980 |
| Selenium | Na2SeO4 | silty clay loam | | 3.7 | 8 | alfalfa | | 1 | 2 | shoot weight | Soltanpour & Workman 1980 |

**Table A.1 (continued)**

| Chemical | Chemical form | Soil type | CEC | % OM | pH | Plant species | DUR (D) | Soil NOEC | Soil LOEC | Growth parameter | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Selenium | Na2SeO4 | silty clay loam | | 3.1 | 8 | alfalfa | | 1 | 2 | shoot weight | Soltanpour & Workman 1980 |
| Selenium | Na2SeO4 | silty clay loam | | 6.3 | 7 | alfalfa | | 2 | 4 | shoot weight | Soltanpour & Workman 1980 |
| Selenium | $Na_2SeO_3$ | sand | 3.25 | 0.2 | 7.9 | wheat | 50 | | 2.5LCT | weight | Singh and Singh 1978 |
| Silver | | surface soil | | | | | | | 2 | | Kabata-Pendias & Pendias 1984 |
| Technetium | TcO4- | silt loam | | 1.4 | 7 | wheat | 30 | 0.1 | 1 | shoot weight | Wildung et al. 1977 |
| Technetium | TcO4- | silt loam | | 1.4 | 7 | soybean | 30 | 0.1 | 1 | shoot weight | Wildung et al. 1977 |
| Thallium | | surface soil | | | | | | | 1 | phytotoxic | Kabata-Pendias & Pendias 1984 |
| Tin | | surface soil | | | | | | | 50 | phytotoxic | Kabata-Pendias & Pendias 1984 |
| Tin | SnCl2 | loam | | | 6 | bush bean | 17 | 50 | 500 | shoot weight | Romney et al. 1975 |
| Uranium | UO2(NO3)2 | sand | 1.2 | | 6 | swiss chard | | | 5 | root weight | Sheppard et al. 1983 |
| Uranium | UO2(NO3)2 | peat | 65 | 92 | 3 | swiss chard | | | 10 | root weight | Sheppard et al. 1983 |
| Vanadium | | surface soil | | | | | | | 2.5 | phytotoxic | EPA 1980 |

Table A.1 (continued)

| Chemical | Chemical form | Soil type | CEC | % OM | pH | Plant species | DUR (D) | Soil NOEC | Soil LOEC | Growth parameter | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Vanadium | | surface soil | | | | | | | 50 | phytotoxic | Kabata-Pendias & Pendias 1984 |
| Zinc | ZnSO4 | surface soil | | | | soybean | | 10 | 25 | seeds/plant | Aery & Sakar 1991 |
| Zinc | ZnSO4 | sandy loam | | | 6 | soybean | | | 131 | leaf weight | White et al. 1979 |
| Zinc | ZnSO4 | sandy loam | | | 7 | soybean | | | 393 | leaf weight | White et al. 1979 |
| Zinc | ZnO | alluvial soil | | | 6 | wheat | | | 1000 | plant weight & grain yield | Muramoto et al. 1990 |
| Zinc | ZnO | alluvial soil | | | 6 | rice | | | 1000 | root weight | Muramoto et al. 1990 |
| Zinc | ZnSO4 | surface soil | | | | coriander | 60 | | 87 | root & shoot weights | Lata and Veer 1990 |
| Zinc | ZnSO4 | surface soil | | | | spinach | 60 | | 87 | root & shoot weights | Lata and Veer 1990 |
| Zinc | ZnSO4 | sand:peat:soil | | | 5 | beech | | | 3.3 | annual ring width | Hagemeyer et al. 1993 |
| Zinc | ZnSO4 | clay loam | | | | cowpea | 30 | 158 | 316 | shoot weight | Gall & Barnette 1940 |
| Zinc | ZnSO4 | clay loam | | | | corn | 30 | 474 | 632 | shoot weight | Gall & Barnette 1940 |
| Zinc | ZnSO4 | sandy loam | | | | cowpea | 30 | 112 | 222 | shoot weight | Gall & Barnette 1940 |

Table A.1 (continued)

| Chemical | Chemical form | Soil type | CEC | % OM | pH | Plant species | DUR (D) | Soil NOEC | Soil LOEC | Growth parameter | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Zinc | ZnSO4 | sandy loam | | | | corn | 30 | 222 | 334 | shoot weight | Gall & Barnette 1940 |
| Zinc | ZnSO4 | sand | | | | corn | 30 | 202 | 404 | shoot weight | Gall & Barnette 1940 |
| Zinc | ZnSO4 | sand | | | | cowpea | 30 | 81 | 141 | shoot weight | Gall & Barnette 1940 |
| Acenapthene | | loam | | 2 | 8 | lettuce | 14 | | 25 | fresh weight shoot | Hulzebos et al. 1993 |
| Biphenyl | | loam | | 2 | 8 | lettuce | 14 | | 68 | fresh weight shoot | Hulzebos et al. 1993 |
| 3-chloroaniline | | loam | | 2 | 7.5 | lettuce | 14 | ca. 7 | 23 | shoot weight | Van Gestel et al. 1996 |
| 3-chlorophenol | | loam | | 2 | 7.5 | lettuce | 14 | ca. 2 | 7 | shoot weight | Van Gestel et al. 1996 |
| 3,4-dichlorophenol | | loam | | 2 | 7.5 | lettuce | 7 | ca. 8 | 25 | shoot weight | Van Gestel et al. 1996 |
| 2,4 Dinitrophenol | | Clay | | | 5 | Fescue | 21 | 20 | 40 | Fresh weight shoot | Overcash et al. 1982 |
| 2,4 Dinitrophenol | | Clay | | | 5 | Corn | 21 | 20 | 40 | Fresh weight shoot | Overcash et al. 1982 |
| 2,4 Dinitrophenol | | Clay | | | 5 | Soybeans | 21 | | 20 | Fresh weight shoot | Overcash et al. 1982 |

Table A.1 (continued)

| Chemical | Chemical form | Soil type | CEC | % OM | pH | Plant species | DUR (D) | Soil NOEC | Soil LOEC | Growth parameter | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2,4 Dinitrophenol | | Sandy loam | | | 4 | Soybean | 21 | 20 | 40 | % seed germination | Overcash et al. 1982 |
| 2,4 Dinitrophenol | | Sandy loam | | | 6 | Fescue | 21 | 60 | 80 | Fresh weight shoot | Overcash et al. 1982 |
| 2,4 Dinitrophenol | | Sandy loam | | | 4 | Corn | 21 | 60 | 80 | % seed germination | Overcash et al. 1982 |
| 2,4 Dinitrophenol | | Sandy loam | | | 4 | Fescue | 21 | 20 | 40 | Fresh weight shoot | Overcash et al. 1982 |
| 2,4 Dinitrophenol | | Sandy loam | | | 6 | Corn | 21 | 20 | 40 | Fresh weight shoot | Overcash et al. 1982 |
| 2,4 Dinitrophenol | | Sandy loam | | | 4 | Soybeans | 21 | 20 | 40 | Fresh weight shoot | Overcash et al. 1982 |
| 2,4 Dinitrophenol | | Sandy loam | | | 4 | Corn | 21 | | 20 | Fresh weight shoot | Overcash et al. 1982 |
| 2,4 Dinitrophenol | | Sandy loam | | | 6 | Soybeans | 21 | | 20 | Fresh weight shoot | Overcash et al. 1982 |
| Di-n-butyl phthalate | | Sandy loam | | | 6 | Corn | 21 | | 200 | Fresh weight shoot | Overcash et al. 1982 |
| Di-n-butyl phthalate | | Sandy loam | | | 6 | Soybeans | 21 | | 200 | Fresh weight shoot | Overcash et al. 1982 |
| Di-n-butyl phthalate | | Sandy loam | | | 6 | Fescue | 21 | 200 | 2000 | Fresh weight shoot | Overcash et al. 1982 |

Table A.1 (continued)

| Chemical | Chemical form | Soil type | CEC | % OM | pH | Plant species | DUR (D) | Soil NOEC | Soil LOEC | Growth parameter | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Di-n-butyl phthalate | | Clay | | | 5 | Corn | 21 | | 200 | Fresh weight shoot | Overcash et al. 1982 |
| Di-n-butyl phthalate | | Clay | | | 5 | Fescue | 21 | 200 | 2000 | Fresh weight shoot | Overcash et al. 1982 |
| Di-n-butyl phthalate | | Sandy loam | | | 4 | Soybean | 21 | | 200 | % seed germination | Overcash et al. 1982 |
| Di-n-butyl phthalate | | Sandy loam | | | 4 | Corn | 21 | | 200 | Fresh weights root & shoot | Overcash et al. 1982 |
| Diethylphthalate | | loam | | 2 | 8 | lettuce | 14 | | 134 | fresh weight shoot | Hulzebos et al. 1993 |
| Furan | | loam | | 2 | 8 | lettuce | 14 | | 617 | fresh weight shoot | Hulzebos et al. 1993 |
| Pentachlorophenol | | loam | | 2 | 8 | lettuce | 14 | | 8 | fresh weight shoot | Hulzebos et al. 1993 |
| Pentachlorophenol | | loam | | 2 | 8 | lettuce | 14 | | 3.2 | fresh weight shoot | Hulzebos et al. 1993 |
| Pentachlorophenol | | sandy loam | | 2.2 | 6.1 | turnip | 14 | | 10 | fresh weight shoot | Gunther and Pestemer 1990 |
| Pentachlorophenol | | sandy loam | | 2.2 | 6.1 | oat | 14 | | 20 | fresh weight shoot | Gunther and Pestemer 1990 |
| Phenol | | loam | | 2 | 8 | lettuce | 14 | | 79 | fresh weight shoot | Hulzebos et al. 1993 |

## Table A.1 (continued)

| Chemical | Chemical form | Soil type | CEC | % OM | pH | Plant species | DUR (D) | Soil NOEC | Soil LOEC | Growth parameter | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Phenol | | loam | | 2 | 8 | lettuce | 14 | | 168 | fresh weight shoot | Hulzebos et al. 1993 |
| PCB - Aroclor 1254 | | Sand | 1.5 | 1 | 5 | Soybean | 26 | 10 | 100 | Fresh weight shoot | Weber & Mrozek 1979 |
| PCB - Aroclor 1254 | | Sand | 1.5 | 1 | 5 | Soybean | 16 | | 1000 | Fresh weight shoot | Strek & Weber 1980 |
| PCB - Aroclor 1254 | | Sand | 1.5 | 1 | 5 | Pigweed | | 40 | 100 | Fresh weight leaves & plant height | Strek & Weber 1980 |
| PCB - Aroclor 1254 | | Sand | 1.5 | 1 | 5 | Soybean | 16 | | 1000 | Fresh weight shoot | Strek & Weber 1980 |
| PCB - Aroclor 1254 | | Sand | 1.5 | 1 | 5 | Pigweed | | 20 | 40 | Fresh weight leaves & plant height | Strek & Weber 1980 |
| PCB - Aroclor 1254 | | Sand | 1.5 | 1 | 5 | Soybean | 16 | | 1000 | Fresh weight leaves & plant height | Strek & Weber 1980 |
| PCB - Aroclor 1254 | | Sand | 1.5 | 1 | 5 | Beet | | | 1000 | Fresh weight leaves & plant height | Strek & Weber 1980 |
| PCB - Aroclor 1254 | | Sand | 1.5 | 1.4 | 4 | Pigweed | 28 | 50 | 100 | Plant height | Strek & Weber 1982b |
| Toluene | | Clay | | | 5 | Soybean | 21 | 2000 | 20,000 | Fresh weight shoot | Overcash et al. 1982 |

Table A.1 (continued)

| Chemical | Chemical form | Soil type | CEC | % OM | pH | Plant species | DUR (D) | Soil NOEC | Soil LOEC | Growth parameter | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Toluene | | Clay | | | 5 | Corn | 21 | | 200 | Fresh weight shoot | Overcash et al. 1982 |
| Toluene | | Sandy loam | | | 4 | Corn | | 2000 | 20,000 | % germination | Overcash et al. 1982 |
| Toluene | | Sandy loam | | | 6 | Corn | 21 | 2000 | 20,000 | Fresh weight shoot | Overcash et al. 1982 |
| Toluene | | Sandy loam | | | 6 | Fescue | 21 | 2000 | 20,000 | Fresh weight shoot | Overcash et al. 1982 |
| Toluene | | Sandy loam | | | 6 | Soybean | 21 | | 200 | Fresh weight shoot | Overcash et al. 1982 |
| Toluene | | Sandy loam | | | 4 | Soybean | | 200 | 2000 | % germination | Overcash et al. 1982 |
| 2,3,5,6-tetrachloroaniline | | loam | | 2 | 7.5 | lettuce | 14 | ca. 5 | 17 | shoot weight | Van Gestel et al. 1996 |
| 2,4,5-trichloroaniline | | loam | | 2 | 7.5 | lettuce | 14 | ca. 7 | 23 | shoot weight | Van Gestel et al. 1996 |
| 2,4,5-trichlorophenol | | loam | | 2 | 7.5 | lettuce | 14 | ca. 1 | 4.3 | shoot weight | Van Gestel et al. 1996 |

# APPENDIX B

# PHYTOTOXICITY DATA DERIVED FROM EXPERIMENTS CONDUCTED IN SOLUTION CULTURE

**Table B.1. Phytotoxicity data derived from experiments conducted in solution culture**
(All chemical concentrations in solutions and plants are mg of the element/L solution;
EXP (D) - Exposure duration in days; LCT - lowest concentration tested)

| Chemical | Form | pH | Plant species | DUR (D) | NOEC | LOEC | Growth parameter | Reference |
|---|---|---|---|---|---|---|---|---|
| Aluminum | | 4.5 | barley | 4 | | 0.0027LCT | root length | Nichol and Oliveira 1995 |
| Aluminum | Al2(SO4)3 | 4.7 | onion | 31 | | 0.05 LCT | root & shoot weight | Wheeler and Follet 1991. |
| Aluminum | Al2(SO4)3 | 4.7 | asparagus | | 0.05 | 0.13 | root & shoot weight | Wheeler and Follet 1991. |
| Aluminum | AlCl3 | 4.5 | wheat | 5 | | 0.14 LCT | root elongation | Sasaki et al. 1994 |
| Aluminum | AlCl3 | 4.5 | wheat | 5 | 0.14 | 0.27 | root elongation | Sasaki et al. 1994 |
| Aluminum | Al2(SO4)3 | 4.7 | squash | 26 | 0.13 | 0.27 | root weight | Wheeler and Follet 1991. |
| Aluminum | $AlCl_3$ | 4.4 | corn | 7 | 0.13 | 0.27 | root elongation and weight | Pintro et al. 1996 |
| Aluminum | $AlCl_3$ | 4.4 | corn | 7 | 0.27 | 0.40 | root elongation | Pintro et al. 1996 |
| Aluminum | AlCl3 | 4.3 | maize | 1 | | 0.54 LCT | root elongation | Llugany et al. 1995 |
| Aluminum | KAl(SO4)2 | 7 | ryegrass | 14 | | 0.63 LCT | length longest root | Wong and Bradshaw 1982. |
| Aluminum | Al2(SO4)3 | 4.3 | lettuce | 42 | 0.54 | 1.1 | air dry weight shoot | Mclean and Gilbert 1927. |
| Aluminum | AlCl3 | 4.3 | maize | 1 | 0.54 | 1.35 | root elongation | Llugany et al. 1995 |
| Aluminum | Al2(SO4)3 | 4.3 | beet | 126 | | 1.8 LCT | air dry weight plant | Mclean and Gilbert 1927. |
| Aluminum | Al2(SO4)3 | 4.3 | beet | 77 | | 1.8 LCT | air dry weight plant | Mclean and Gilbert 1927. |
| Aluminum | Al2(SO4)3 | 4.3 | barley | 77 | | 1.8 LCT | air dry weight root/shoot | Mclean and Gilbert 1927. |

Table B.1 (continued)

| Chemical | Form | pH | Plant species | DUR (D) | NOEC | LOEC | Growth parameter | Reference |
|---|---|---|---|---|---|---|---|---|
| Aluminum | Al2(SO4)3 | 4.3 | rye | 63 | | 1.8 LCT | air dry weight root | Mclean and Gilbert 1927. |
| Aluminum | Al2(SO4)3 | 4.3 | beet | 126 | | 1.8 LCT | air dry weight plant | Mclean and Gilbert 1927. |
| Aluminum | Al2(SO4)3 | 4.3 | lettuce | 56 | 0.9 | 1.8 | air dry weight plant | Mclean and Gilbert 1927. |
| Aluminum | Al2(SO4)3 | 4 | citrange | 60 | 0.11 | 2.7 | root length | Lin and Myhre 1991. |
| Aluminum | Al2(SO4)3 | | rice | 13 | 0.27 | 2.7 | root & shoot weight | Wallace and Romney 1977a. |
| Aluminum | Al2(SO4)3 | | soybean | 13 | 0.27 | 2.7 | leaf weight | Wallace and Romney 1977a. |
| Aluminum | Al2(SO4)3 | 4.3 | lettuce | 56 | 1.8 | 2.7 | air dry weight plant | Mclean and Gilbert 1927. |
| Aluminum | Al2(SO4)3 | 4.5 | rye | 70 | | 3.6 LCT | air dry weight root | Mclean and Gilbert 1927. |
| Aluminum | Al2(SO4)3 | 4.3 | radish | 77 | 1.8 | 3.6 | air dry weight root/shoot | Mclean and Gibert 1927. |
| Aluminum | Al2(SO4)3 | 4.3 | carrot | 126 | | 3.6 LCT | air dry weight plant | Mclean and Gilbert 1927. |
| Aluminum | Al2(SO4)3 | 4.3 | carrot | 126 | | 3.6 LCT | air dry weight plant | Mclean and Gilbert 1927. |
| Aluminum | AlCl3 | 4 | Norway Spruce | 8 | 1.4 | 5.4 | root elongation | Godbold & Kettner 1991 |
| Aluminum | AlCl3 | 4.3 | barley | 30 | 4 | 6 | root & shoot weight | Macleod and Jackson 1967. |
| Aluminum | Al2(SO4)2 | 4.3 | turnip | 77 | 3.6 | 7.2 | air dry weight shoot | Mclean and Gilbert 1927. |
| Aluminum | Al2(SO4)3 | 4.3 | oat | 63 | 3.6 | 7.2 | air dry weight root/shoot | Mclean and Gilbert 1927. |
| Aluminum | AL2(SO4)3 | 4.3 | cabbage | 98 | | 7.2 LCT | air dry weight plant | Mclean and Gilbert 1927. |
| Aluminum | AlCl3 | 3.5 | Douglas fir | 279 | 4 | 8 | shoot weight | Keltjens 1990. |

Table B.1 (continued)

| Chemical | Form | pH | Plant species | DUR (D) | NOEC | LOEC | Growth parameter | Reference |
|---|---|---|---|---|---|---|---|---|
| Aluminum | AlCl3+Al(NO3)3 | 3.8 | spruce | 21 | 5.4 | 8.1 | growth rate root | Goransson & Eldhuset 1991 |
| Aluminum | Al2(SO4)3 | 4 | lemon | 60 | 4.8 | 8.3 | fresh weight; root length | Lin and Myhre 1991. |
| Aluminum | Al2(SO4)3 | 4 | orange | 60 | 4.8 | 8.3 | fresh weight; root length | Lin and Myhre 1991. |
| Aluminum | Al2(SO4)3 | 4 | citrumelo | 60 | 4.8 | 8.3 | fresh weight plant | Lin and Myhre 1991. |
| Aluminum | Al2(SO4)3 | 4.3 | barley | 30 | 8 | 10 | root & shoot weight | Macleod and Jackson 1967. |
| Aluminum | $AlCl_3$ | 4.5 | perennial grass | 16 | 2.2 | 12.9 | root length | Zavas et al. 1996 |
| Aluminum | $AlCl_3$ | 4.5 | perennial grass | 16 | 2.2 | 12.9 | root length | Zavas et al. 1996 |
| Aluminum | Al2(SO4)3 | 4 | orange | 60 | 8.3 | 24.4 | fresh weight; root length | Lin and Myhre 1991. |
| Aluminum | AlCl3 | 3.5 | Douglas fir | 279 | 16 | 32 | root weight & length | Keltjens 1990. |
| Aluminum | AlCl3+Al(NO3)3 | 3.8 | pine | 21 | 162 | 269.8 | growth rate shoot | Goransson & Eldhuset 1991 |
| Arsenic | As2O3 | | cluster bean | | | 0.001 LCT | root length | Mhatre & Chaphekar 1982. |
| Arsenic | As2O3 | | radish | | .001 | 0.01 | root length | Mhatre & Chaphekar 1982. |
| Arsenic | | | | | | 0.02 LCT | | Bowen 1979. |
| Arsenic | As2O3 | | alfalfa | | 0.1 | 1 | root & shoot lengths | Mhatre & Chaphekar 1982. |
| Arsenic | As2O3 | | mung bean | | 0.1 | 1 | root & shoot lengths | Mhatre & Chaphekar 1982. |
| Arsenic | Na2HAsO4 | 7.3 | mustard | 3 | | 5.5 EC50 | root length | Fargasova 1994. |
| Arsenic | Na2HAsO4 | 7.3 | mustard | 3 | | 30 LC50 | seed germination | Fargasova 1994. |

Table B.1 (continued)

| Chemical | Form | pH | Plant species | DUR (D) | NOEC | LOEC | Growth parameter | Reference |
|---|---|---|---|---|---|---|---|---|
| Beryllium | | 5.3 | bush bean | 48 | | 0.5 LCT | plant weight | Romney et al. 1962. |
| Beryllium | BeSO4 | | lettuce | 3 | | 0.5 LCT | radicle length | Carlson et al. 1991. |
| Beryllium | BeSO4 | | turnip | 3 | | 0.5 LCT | radicle length | Carlson et al. 1991. |
| Beryllium | BeCl2 | 5.3 | barley | 20 | | 2 LCT | plant weight | Romney & Childress 1965. |
| Beryllium | BeCl2 | 5.3 | pea | 24 | | 2 LCT | plant weight | Romney & Childress 1965. |
| Beryllium | BeCl2 | 5.3 | lettuce | 28 | | 2 LCT | plant weight | Romney & Childress 1965. |
| Beryllium | BeSO4 | | cabbage | 3 | 1 | 2.5 | radicle length | Carlson et al. 1991. |
| Beryllium | BeCl2 | 5.3 | alfalfa | 54 | 2 | 4 | plant weight | Romney & Childress 1965. |
| Beryllium | BeSO4 | | radish | 3 | 2.5 | 5 | radicle length | Carlson et al. 1991. |
| Beryllium | BeSO4 | | wheat | 3 | 10 | 20 | radicle length | Carlson et al. 1991. |
| Beryllium | BeSO4 | | millet | 3 | 30 | 40 | radicle length | Carlson et al. 1991. |
| Bismuth | | | | | | 27 | phytotoxic | Bowen 1979. |
| Boron | | | | | | 1 | | Bowen 1979. |
| Boron | H3BO3 | | bush beans | 16 | 1.1 | 5.4 | root & leaf weights | Wallace et al. 1977b. |
| Bromine | | | | | | 15 | phytotoxic | Martin 1966a. |
| Cadmium | Cd-acetate | | perennial ryegrass | 21 | | 0.001LCT | root dry weight | Al-Attar et al. 1988 |
| Cadmium | CdCl2 | 6.3 | carrot | 35 | | 0.01 LCT | shoot weight | Turner 1973. |
| Cadmium | Cd(NO3)2 | 6.2 | soybeans | 21 | | 0.05 LCT | root & leaf weights | Cunningham 1977. |

Table B.1 (continued)

| Chemical | Form | pH | Plant species | DUR (D) | NOEC | LOEC | Growth parameter | Reference |
|---|---|---|---|---|---|---|---|---|
| Cadmium | | 5.2 | soybean | 21 | | 0.05 LCT | | Cunningham et al. 1975. |
| Cadmium | $CdCl_2$ | | birch | 8 | 0.022 | 0.056 | shoot growth rate | Gussarsson 1996 |
| Cadmium | CdCl2 | 5.5 | corn | 58 | 0.01 | 0.1 | plant weight & grain yield | Iwai et al. 1975. |
| Cadmium | CdSO4 | | bean | 21 | | 0.1 LCT | plant weight | Page et al. 1972. |
| Cadmium | CdSO4 | | turnip | 21 | | 0.1 LCT | plant weight | Page et al. 1972. |
| Cadmium | CdSO4 | | beet | 21 | | 0.1 LCT | plant weight | Page et al. 1972. |
| Cadmium | CdCl2 | 6.3 | tomato | 14 | 0.01 | 0.1 | shoot weight | Turner 1973. |
| Cadmium | CdSO4 | | giant endive | 35 | | 0.1 LCT | root & weights | Garate et al. 1993. |
| Cadmium | CdCl2 | 5.5 | wheat | 13 | | 0.1 LCT | shoot weight | Jalil et al. 1994 |
| Cadmium | CdSO4 | 4 | Norway spruce | 7 | | 0.112 LCT | root length | Lamersdorf et al. 1991. |
| Cadmium | CdSO4 | | chrysanthemum | 21 | | 0.112 LCT | root & stem weights | Patel et al. 1976. |
| Cadmium | CdSO4 | | corn | 10 | | 0.112 LCT | fresh plant weight | Stiborova et al. 1986. |
| Cadmium | CdSO4 | | corn | 21 | 0.25 | 0.5 | plant weight | Page et al. 1972. |
| Cadmium | CdSO4 | 4.3 | Norway Spruce | 7 | | 0.56 LCT | root elongation | Godbold & Huttermann 1985 |
| Cadmium | CdCl2 | | lettuce | 14 | | 0.84 EC50 | fresh shoot weight | Adema and Henzen 1989. |
| Cadmium | CdCl2 | 5.5 | corn | 19 | 0.1 | 1 | plant weight | Iwai et al. 1975. |
| Cadmium | CdCl2 | 6.3 | swiss chard | 35 | 0.1 | 1 | shoot weight | Turner 1973. |
| Cadmium | CdSO4 | | tomato | 21 | | 1 LCT | plant weight | Page et al. 1972. |

Table B.1 (continued)

| Chemical | Form | pH | Plant species | DUR (D) | NOEC | LOEC | Growth parameter | Reference |
|---|---|---|---|---|---|---|---|---|
| Cadmium | CdSO4 | | pepper | 21 | | 1 LCT | plant weight | Page et al. 1972. |
| Cadmium | CdSO4 | | barley | 21 | | 1 LCT | plant weight | Page et al. 1972. |
| Cadmium | CdSO4 | | lettuce | 21 | | 1 LCT | plant weight | Page et al. 1972. |
| Cadmium | CdCl2 | 6.3 | beetroot | 35 | 0.1 | 1 | shoot weight | Turner 1973. |
| Cadmium | CdSO4 | | sesame | 7 | | 1.1 LCT | root growth | Inouhe et al. 1994 |
| Cadmium | CdSO4 | | pea | 7 | | 1.1 LCT | root growth | Inouhe et al. 1994 |
| Cadmium | CdSO4 | | radish | 7 | | 1.1 LCT | root growth | Inouhe et al. 1994 |
| Cadmium | CdSO4 | | cucumber | 7 | | 1.1 LCT | root growth | Inouhe et al. 1994 |
| Cadmium | CdSO4 | | tomato | 7 | | 1.1 LCT | root growth | Inouhe et al. 1994 |
| Cadmium | CdSO4 | | Azuki bean | 7 | | 1.1 LCT | root growth | Inouhe et al. 1994 |
| Cadmium | CdSO4 | 5.5 | cotton | | | 1.12 LCT | plant weight | Rehab and Wallace 1978. |
| Cadmium | $Cd(NO_3)_2$ | 6.5 | maize | 17 | | 1.12LCT | stalk weight | Kummerova and Brandejsova 1994 |
| Cadmium | CdSO4 | 7 | ryegrass | 14 | | 1.25 LCT | longest root & shoot | Wong and Bradshaw 1982. |
| Cadmium | CdCl2 | | rice | 6 | | 1.4 EC50 | radicle weight | Wang 1994 |
| Cadmium | CdCl2 | 4 | corn | 12 | 0.2 | 2 | plant weight | Iwai et al. 1975. |
| Cadmium | CdCl2 | 5 | corn | 12 | 0.2 | 2 | plant weight | Iwai et al. 1975. |
| Cadmium | CdCl2 | 6 | corn | 12 | 0.2 | 2 | plant weight | Iwai et al. 1975. |

**Table B.1 (continued)**

| Chemical | Form | pH | Plant species | DUR (D) | NOEC | LOEC | Growth parameter | Reference |
|---|---|---|---|---|---|---|---|---|
| Cadmium | $CdCl_2$ | 6.5 | sugar beet | 14 | 0.56 | 2.25 | shoot and whole plant weight | Greger et al. 1991 |
| Cadmium | CdSO4 | | cabbage | 21 | 1 | 2.5 | plant weight | Page et al. 1972. |
| Cadmium | CdCl2 | | tomato | 14 | 1.1 | 3 EC50 | fresh shoot weights | Adema and Henzen 1989. |
| Cadmium | CdSO4 | | lettuce | 7 | 1.1 | 3.4 | root growth | Inouhe et al. 1994 |
| Cadmium | CdSO4 | | barley | 7 | 1.1 | 3.4 | root growth | Inouhe et al. 1994 |
| Cadmium | CdCl2 | | broad bean | 3 | 4 | 6 | root length | Misra et al. 1994 |
| Cadmium | CdCl2 | | oat | 14 | | 6 EC50 | fresh shoot weight | Adema and Henzen 1989. |
| Cadmium | CdSO4 | | oats | 7 | 3.4 | 6.8 | rootgrowth | Inouhe et al. 1994 |
| Cadmium | CdSO4 | 5 | bean | 15 | 0.11 | 11 | root & leaf weights | Wallace 1979. |
| Cadmium | Cd(NO3)2 | | corn | 18 | 11.2 | 28.1 | root & shoot lengths | Rascio et al. 1993. |
| Cadmium | $Cd(NO_3)_2$ | | wheat | 7 | | 29.8LCT | root and shoot length and mass | Ouzounidou et al. 1997 |
| Cadmium | CdCl2 | | maize | 5 | | 45 LCT | seed germination, radicle length, & plant weight | El-Enany 1995 |
| Cadmium | CdCl2 | 6.6 | mustard | 3 | | 48 EC50 | root length | Fargasova 1994. |
| Cadmium | CdCl2 | 6.6 | mustard | 3 | | 692 LC50 | seed germination | Fargasova 1994. |
| Chromium | CrSO4 | | chrysanthemum | 21 | | 0.052 LCT | stem & leaf weights | Patel et al. 1976. |
| Chromium | K2Cr2O7 | | lettuce | 14 | .004 | 0.16 EC50 | fresh shoot weight | Adema and Henzen 1989. |

Table B.1 (continued)

| Chemical | Form | pH | Plant species | DUR (D) | NOEC | LOEC | Growth parameter | Reference |
|---|---|---|---|---|---|---|---|---|
| Chromium | K2Cr2O7 | | tomato | 14 | 0.11 | 0.29 EC50 | fresh shoot weight | Adema and Henzen 1989. |
| Chromium | K2Cr2O7 | | bush beans | 11 | | 0.54 LCT | leaf weight | Wallace et al. 1977a. |
| Chromium | K2Cr2O7 | | soybean | 5 | 0.5 | 1 | shoot weight | Turner and Rust 1971. |
| Chromium | K2Cr2O7 | | oat | 14 | 0.12 | 1.4 EC50 | fresh shoot weight | Adema and Henzen 1989. |
| Chromium | K2Cr2O7 | 7 | ryegrass | 14 | | 2.5 LCT | root length | Wong and Bradshaw 1982. |
| Chromium | K2CrO4 | | rice | 6 | | 4.8 EC50 | radicle Weight | Wang 1994 |
| Chromium | CrCl3+K2CrO4 | 5 | cabbage | 55 | 2 | 10 | plant weight | Hara et al. 1976. |
| Chromium | (NH4)2CrO4 | 7.3 | mustard | 3 | | 46 EC50 | root length | Fargasova 1994. |
| Chromium | Cr2(SO4)3 | | rye grass | 2.5 | 10 | 50 | % seed gemination | Breeze 1973. |
| Chromium | Cr2K2O7 | | ryegrass | 2.5 | 10 | 50 | % seed germination | Breeze 1973. |
| Chromium | CrCl3 | | tomato | | 50 | 100 | root weight and length | Moral et al. 1995 |
| Chromium | (NH4)2CrO4 | 7.3 | mustard | 3 | | 100 LC50 | seed germination | Fargasova 1994. |
| Cobalt | CoSO4 | | bush beans | 21 | | 0.06 LCT | leaf weight | Wallace et al. 1977a. |
| Cobalt | CoSO4 | | chrysanthemum | 21 | | 0.06 LCT | root weight | Patel et al. 1976. |
| Cobalt | CoSO4 | 5 | honeysuckle | 20 | 1 | 5 | radicle elongation | Patterson & Olson 1983 |
| Cobalt | CoSO4 | 5 | paper birch | 20 | 1 | 5 | radicle elongation | Patterson & Olson 1983 |
| Cobalt | CoCl2 | | broad bean | 3 | 8 | 10 | root elongation | Misra et al. 1994 |
| Cobalt | CoSO4 | 5 | black spruce | 20 | 5 | 10 | radicle elongation | Patterson & Olson 1983 |

**Table B.1 (continued)**

| Chemical | Form | pH | Plant species | DUR (D) | NOEC | LOEC | Growth parameter | Reference |
|---|---|---|---|---|---|---|---|---|
| Cobalt | CoSO4 | 5 | jack pine | 20 | 10 | 20 | radicle elongation | Patterson & Olson 1983 |
| Cobalt | CoSO4 | 5 | red pine | 20 | 10 | 20 | radicle elongation | Patterson & Olson 1983 |
| Cobalt | CoSO4 | 5 | white spruce | 20 | 20 | 50 | radicle elongation | Patterson & Olson 1983 |
| Cobalt | CoSO4 | 5 | white pine | 20 | 50 | 100 | radicle elongation | Patterson & Olson 1983 |
| Copper | CuSO4 | | ryegrass | 14 | | 0.031 LCT | length longest root | Wong and Bradshaw 1982. |
| Copper | CuSO4 | | corn | 10 | | 0.064 LCT | fresh plant weight | Stiborova et al. 1986. |
| Copper | CuSO4 | | chrysanthemum | 21 | | 0.064 | root weight | Patel et al. 1976. |
| Copper | CuCl2 | | rice | 6 | | 0.22 EC50 | radicle weight | Wang 1994 |
| Copper | $CuSO_4$ | | maize | 14 | 0.45 | 0.64 | shoot length | Mocquot et al. 1996 |
| Copper | CuSO4 | 5 | paper birch | 20 | 0.5 | 1 | radicle elongation | Patterson & Olson 1983 |
| Copper | CuSO4 | 6.1 | honeysuckle | 110 | | 4 LCT | stem dia increase; plant weight | Heale and Ormrod 1982. |
| Copper | CuSO4 | 6.1 | dogwood | 110 | | 4 LCT | stem dia increase; plant weight | Heale and Ormrod 1982. |
| Copper | CuSO4 | 6.1 | red pine | 110 | | 4 LCT | plant weight | Heale and Ormrod 1982. |
| Copper | CuSO4 | 5 | black spruce | 20 | 1 | 5 | radicle elongation | Patterson & Olson 1983 |
| Copper | CuSo4 | 5 | red pine | 20 | 1 | 5 | radicle elongation | Patterson & Olson 1983 |
| Copper | CuSO4 | 5 | jack pine | 20 | 5 | 10 | radicle elongation | Patterson & Olson 1983 |
| Copper | CuSO4 | 6.1 | maple | 110 | 2 | 10 | plant weight | Heale and Ormrod 1982. |

Table B.1 (continued)

| Chemical | Form | pH | Plant species | DUR (D) | NOEC | LOEC | Growth parameter | Reference |
|---|---|---|---|---|---|---|---|---|
| Copper | CuSO4 | 5 | white spruce | 20 | 10 | 20 | radicle elongation | Patterson & Olson 1983 |
| Copper | CuSO4 | 5 | honeysuckle | 20 | 20 | 50 | radicle elongation | Patterson & Olson 1983 |
| Copper | CuSO4 | | rice | 4 | 6.4 | 64 | root length | Gupta and Mukherji 1977. |
| Copper | CuSO4 | 5 | white pine | 20 | 50 | 100 | radicle elongation | Patterson & Olson 1983 |
| Fluorine | | | | | | 5 | | Bowen 1979. |
| Iodine | KI | 5.8 | corn | 60 | 0.1 | 0.5 | shoot weight | Lewis and Powers 1941. |
| Iodine | KI | | tomato | 60 | 0.5 | 5 | shoot weight | Newton and Toth 1952. |
| Iron | | | | | | 10 LCT | | Wallihan 1966. |
| Iron | FeSO4 | | bush bean | 15 | 11.2 | 28 | root, leaf & stem weights | Wallace et al. 1977b. |
| Iron | FeSO4 | 5 | cabbage | 55 | 10 | 50 | plant weight | Hara et al. 1976. |
| Lead | Pb(NO3)2 | | cluster bean | | | 0.001 LCT | root length | Mhatre & Chaphekar 1982. |
| Lead | PbCl2 | 4 | Norway Spruce | 8 | | 0.021 LCT | root elongation | Godbold & Kettner 1991 |
| Lead | PbCl2 | 4 | Norway spruce | 7 | | 0.021 LCT | root length | Lamersdorf et al. 1991. |
| Lead | Pb(NO3)2 | | alfalfa | | 0.01 | 0.1 | root length | Mhatre & Chaphekar 1982. |
| Lead | Pb(NO3)2 | | onion | 4 | 0.02 | 0.21 | root growth | Liu et al. 1994 |
| Lead | Pb(NO3)2 | | mung bean | | 0.1 | 1 | root length | Mhatre & Chaphekar 1982. |
| Lead | Pb(NO3)2 | | radish | | 0.1 | 1 | shoot length | Mhatre & Chaphekar 1982. |

Table B.1 (continued)

| Chemical | Form | pH | Plant species | DUR (D) | NOEC | LOEC | Growth parameter | Reference |
|---|---|---|---|---|---|---|---|---|
| Lead | | | barley | 7 | 1 | 2 | root length | Wierzbicka & Antosiewicz 1993 |
| Lead | | | maize | 7 | | 1 LCT | root length | Wierzbicka & Antosiewicz 1993 |
| Lead | Pb(NO3)2 | | ryegrass | 14 | | 2.5 LCT | root & shoot lengths | Wong and Bradshaw 1982. |
| Lead | Pb(C2H3O2)2 | | rice | 6 | | 9.7 EC50 | radicle weight | Wang 1994 |
| Lead | Pb(NO3)2 | | wire grass | 14 | | 10 LCT | root length | Wong and Lau 1985. |
| Lead | Pb(NO3)2 | | Bermuda grass | 14 | | 10 LCT | root length | Wong and Lau 1985. |
| Lead | Pb(NO3)2 | | Bermuda grass | 14 | | 10 LCT | root length | Wong and Lau 1985. |
| Lead | Pb(NO3)2 | | wire grass | 14 | | 10 LCT | root length | Wong and Lau 1985. |
| Lead | Pb(NO3)2 | | Bermuda grass | 14 | | 10 LCT | root length | Wong and Lau 1985. |
| Lead | PbSO4 | | french bean | 28 | 5 | 10 | plant weight | Hooper 1937. |
| Lead | PbSO4 | | french bean | 28 | 5 | 10 | plant weight | Hooper 1937. |
| Lead | PbSO4 | | french bean | 28 | 5 | 10 | plant weight | Hooper 1937. |
| Lead | Pb(NO3)2 | | wire grass | 14 | 10 | 20 | root length | Wong and Lau 1985. |
| Lead | PbSO4 | | french bean | 28 | 20 | 30 | plant weight | Hooper 1937. |
| Lead | PbSO4 | | french bean | 28 | 20 | 30 | plant weight | Hooper 1937. |
| Lead | Pb(NO3)2 | | corn | 10 | 20.7 | 207 | fresh plant weight | Stiborova et al. 1986. |
| Lead | Pb(CH3COO)2 | 5.5 | mustard | 3 | | 263 EC50 | root length | Fargasova 1994. |

Table B.1 (continued)

| Chemical | Form | pH | Plant species | DUR (D) | NOEC | LOEC | Growth parameter | Reference |
|---|---|---|---|---|---|---|---|---|
| Lead | Pb(CH3COO)2 | 5.5 | mustard | 3 | | 1148 LC50 | seed germination | Fargasova 1994. |
| Lithium | LiNO3 | | bush beans | 24 | | 3.5 LCT | stem weight | Wallace et al. 1977c. |
| Manganese | MnSO4 | 7 | ryegrass | 14 | | 0.75 LCT | length longest root | Wong and Bradshaw 1982. |
| Manganese | MnSO4 | 4.6 | cotton | 18 | | 4 LCT | root & leaf weight | Foy et al. 1995 |
| Manganese | MnSO4 | 5 | cotton | 18 | | 4 LCT | root & leaf weight | Foy et al. 1995 |
| Manganese | MnSO4 | | bush beans | 16 | | 5.5 LCT | root, leaf & stem weights | Wallace et al. 1977b. |
| Manganese | MnSO4 | 5.5 | tomato | 17 | 2.8 | 5.5 | plant weight | Le Bot et al. 1990. |
| Manganese | MnSO4 | 5 | cotton | 18 | 4 | 8 | root & leaf weight | Foy et al. 1995 |
| Manganese | MnSO4 | 4.6 | cotton | 18 | 8 | 16 | root & leaf weight | Foy et al. 1995 |
| Manganese | MnSO4 | 4.8 | wheat | 30 | | 30 LCT | root weight | Burke et al. 1990. |
| Manganese | MnSO4 | 4.8 | wheat | 30 | | 30 LCT | root weight | Burke et al. 1990. |
| Manganese | MnSO4 | 4.8 | wheat | 30 | | 30 LCT | root & shoot weights | Burke et al. 1990. |
| Manganese | MnSO4 | 4.8 | wheat | 30 | | 30 LCT | root weight | Burke et al. 1990. |
| Manganese | MnSO4 | 6 | spruce | 32 | 11 | 44 | root length | Langeheinrich et al. 1992. |
| Manganese | MnSO4 | 6 | spruce | 32 | 11 | 44 | growth rate | Langheinrich et al. 1992. |
| Manganese | | | potato | 32 | | 33.5 LCT | fresh shoot weight | Marsh and Peterson 1990. |
| Manganese | MnSO4 | 4 | spruce | 77 | | 44 LCT | height epicotyl | Langheinrich et al. 1992. |
| Manganese | MnSO4 | 4 | spruce | 77 | | 44 LCT | height epicotyl | Langheinrich et al. 1992. |

Table B.1 (continued)

| Chemical | Form | pH | Plant species | DUR (D) | NOEC | LOEC | Growth parameter | Reference |
|---|---|---|---|---|---|---|---|---|
| Manganese | MnSO4 | | bush beans | 21 | 5.5 | 55 | root, leaf & stem weights | Wallace et al. 1977b. |
| Manganese | MnSO4 | 4.8 | wheat | 30 | 30 | 90 | root & shoot weights | Burke et al. 1990. |
| Manganese | MnCl2 | | rice | 6 | | 100 EC50 | radicle weight | Wang 1994 |
| Mercury | HgCl2 | 4 | Norway spruce | 7 | | 0.002 LCT | root length | Lamersdorf et al. 1991. |
| Mercury | HgCl2 | | alfalfa | | .001 | 0.01 | root & shoot lengths | Mhatre & Chaphekar 1982. |
| Mercury | HgCl2 | | Pennisetum | | .001 | 0.01 | root & shoot lengths | Mhatre & Chaphekar 1982. |
| Mercury | HgCl2 | | mustard | | .001 | 0.01 | root length | Mhatre & Chaphekar 1982. |
| Mercury | HgCl2 | | cluster bean | | .001 | 0.01 | root & shoot lengths | Mhatre & Chaphekar 1982. |
| Mercury | HgCl2 | | sorghum | | .001 | 0.01 | root length | Mhatre & Chaphekar 1982. |
| Mercury | HgCl2 | | radish | | .001 | 0.01 | root & shoot lengths | Mhatre & Chaphekar 1982. |
| Mercury | HgCl2 | 4.3 | Norway spruce | 7 | | 0.02 LCT | root elongation | Godbold & Huttermann 1985 |
| Mercury | HgCl2 | 4.3 | spruce | 35 | | 0.02 LCT | needle chlorophyll | Schlegel et al. 1987. |
| Mercury | HgCl2 | | mung bean | | .01 | 0.1 | root & shoot lengths | Mhatre & Chaphekar 1982. |
| Mercury | HgCl2 | | pea | 5 | 0.1 | 1 | seed germination, root length | Mhatre & Chaphekar 1982. |
| Mercury | HgCl2 | 6 | tobacco | 10 | 0.1 | 1 | root & shoot weight | Suszcynsky & Shann 1995 |
| Mercury | HgCl2 | 7 | ryegrass | 14 | | 5 LCT | root & shoot lengths | Wong and Bradshaw 1982. |
| Mercury | HgCl2 | 7.4 | mustard | 3 | | 9.3 EC50 | root length | Fargasova 1994. |

Table B.1 (continued)

| Chemical | Form | pH | Plant species | DUR (D) | NOEC | LOEC | Growth parameter | Reference |
|---|---|---|---|---|---|---|---|---|
| Mercury | Hg2Cl2 | | barley | 7 | 10 | 50 | root length & plant weight | Mukhiya et al. 1983. |
| Mercury | HgCl2 | | barley | 7 | 10 | 50 | root&shoot length, plant weight | Mukhiya et al. 1983. |
| Mercury | HgCl2 | 7.4 | mustard | 3 | | 129 LC50 | seed germination | Fargasova 1994. |
| Mercury | CH3HgCl | 4 | Norway spruce | 7 | | 0.0002 LCT | root length | Lamersdorf et al. 1991. |
| Mercury | CH3HgCl | 4.3 | spruce | 35 | | 0.002 LCT | transpiration rate/$CO_2$ uptake | Schlegel et al. 1987. |
| Mercury | CH3HgCl | 4.3 | spruce | 35 | | 0.02 LCT | needle chlorophyll | Schlegel et al. 1987. |
| Mercury | C8H8HgO2 | | barley | 7 | 1 | 5 | shoot length & plant weight | Mukhiya et al. 1983. |
| Mercury | C4H6HgO4 | | barley | 7 | 5 | 10 | root length & plant weight | Mukhiya et al. 1983. |
| Molybdenum | | | | | | 0.5 LCT | phytotoxic | Johnson 1966. |
| Molybdenum | H2MoO4 | 5 | bean | 14 | | 9.6 LCT | leaf weight | Wallace 1979. |
| Molybdenum | H2MoO4 | | bush beans | 14 | | 9.6 LCT | leaf weight | Wallace et al. 1977b. |
| Nickel | Ni(NH4)2(SO4)2 | 7 | ryegrass | 14 | | 0.13 LCT | length longest root | Wong and Bradshaw 1982. |
| Nickel | NiSO4 | | chrysanthemum | 21 | 0.06 | 0.59 | stem & leaf weights | Patel et al. 1976. |
| Nickel | NiCl2 | | rice | 6 | | 0.85 EC50 | radicle weight | Wang 1994 |
| Nickel | NiSO4 | 5 | paper birch | 20 | 0.5 | 1 | radicle elongation | Patterson & Olson 1983 |

Table B.1 (continued)

| Chemical | Form | pH | Plant species | DUR (D) | NOEC | LOEC | Growth parameter | Reference |
|---|---|---|---|---|---|---|---|---|
| Nickel | NiSO4 | | lettuce | 3 | 0.5 | 1 | radicle length | Carlson et al. 1991. |
| Nickel | NiSO4 | | turnip | 3 | 0.5 | 1 | radicle length | Carlson et al. 1991. |
| Nickel | NiSO4 | 5 | bush beans | 21 | | 1.17 LCT | root & leaf weights | Wallace 1979. |
| Nickel | NiSO4 | | cabbage | 3 | 1 | 2 | radicle length | Carlson et al. 1991. |
| Nickel | NiSO4 | 6.1 | honeysuckle | 110 | | 2 LCT | stem dia increase; plant weight | Heale and Ormrod 1982. |
| Nickel | NiSO4 | 6.1 | red pine | 110 | | 2 LCT | stem dia increase; plant weight | Heale and Ormrod 1982. |
| Nickel | NiSO4 | 5 | jack pine | 20 | 1 | 5 | radicle elongation | Patterson & Olson 1983 |
| Nickel | NiSO4 | 5 | red pine | 20 | 1 | 5 | radicle elongation | Patterson & Olson 1983 |
| Nickel | NiSO4 | 5 | black spruce | 20 | 1 | 5 | radicle elongation | Patterson & Olson 1983 |
| Nickel | NiSO4 | 5 | honeysuckle | 20 | 1 | 5 | radicle elongation | Patterson & Olson 1983 |
| Nickel | NiSO4 | 6 | cotton | | 0.59 | 5.9 | plant weight | Rehab and Wallace 1978. |
| Nickel | NiCl2 | | broad bean | 3 | 6 | 8 | root length | Misra et al. 1994 |
| Nickel | NiSO4 | | wheat | 3 | 4 | 8 | radicle length | Carlson et al. 1991. |
| Nickel | NiSO4 | | radish | 3 | 4 | 8 | radicle length | Carlson et al. 1991. |
| Nickel | NiSO4 | 6.1 | dogwood | 110 | 2 | 10 | stem dia increase; plant weight | Heale and Ormrod 1982. |
| Nickel | NiSO4 | 6.1 | maple | 110 | 2 | 10 | plant weight | Heale and Ormrod 1982. |
| Nickel | NiSO4 | | millet | 3 | 8 | 12 | radicle length | Carlson et al. 1991. |

Table B.1 (continued)

| Chemical | Form | pH | Plant species | DUR (D) | NOEC | LOEC | Growth parameter | Reference |
|---|---|---|---|---|---|---|---|---|
| Nickel | NiSO4 | 5 | white spruce | 20 | 10 | 20 | radicle elongation | Patterson & Olson 1983 |
| Nickel | NiSO4 | 5 | white pine | 20 | 20 | 50 | radicle elongation | Patterson & Olson 1983 |
| Selenium | $Na_2SeO_4$ | | bermudagrass | 21 | | 0.5LCT | root length, shoot height | Wu et al. 1988 |
| Selenium | Na2SeO4 | 4.4 | bush bean | | | 0.79 LCT | root weight | Wallace et al. 1980. |
| Selenium | Na2SeO3 | | wheat | 42 | | 1 LCT | root&shoot weight, plant height | Martin 1937a. |
| Selenium | Na2SeO3 | | buckwheat | 42 | | 1 LCT | root&shoot weight, plant height | Martin 1937a. |
| Selenium | $Na_2SeO_4$ | | crested wheatgrass | 21 | 0.5 | 1 | root length, shoot height | Wu et al. 1988 |
| Selenium | $Na_2SeO_4$ | | seaside bentgrass | 21 | 0.5 | 1 | root length, shoot height | Wu et al. 1988 |
| Selenium | $Na_2SeO_4$ | | buffalograss | 21 | 1 | 2 | root length, shoot height | Wu et al. 1988 |
| Selenium | $Na_2SeO_4$ | 6.7 | Indian mustard | 60 | | 2LCT | root and shoot dry weight | Banuelos et al. 1997 |
| Selenium | $Na_2SeO_4$ | 6.7 | Brassica carinata | 60 | | 2LCT | root and shoot dry weight | Banuelos et al. 1997 |
| Selenium | Na2SeO3 | | milk-vetch | | 9 | 27 | plant weight | Trelease & Trelease 1938. |
| Silver | AgNO3 | 5 | bush bean | 13 | | 0.17 LCT | leaf weight | Wallace 1979. |

Table B.1 (continued)

| Chemical | Form | pH | Plant species | DUR (D) | NOEC | LOEC | Growth parameter | Reference |
|---|---|---|---|---|---|---|---|---|
| Silver | AgNO3 | | rice | 6 | | 0.55 EC50 | radicle weight | Wang 1994 |
| Technetium | TcO4- | 5.5 | soybean | 20 | 0.04 | 0.2 | fresh weight seedlngs | Berlyn et al. 1980. |
| Technetium | NH4TcO4 | | wheat | 10 | 0.03 | 0.3 | shoot weight | Gast et al. 1978. |
| Technetium | NH4TcO4 | | barley | 10 | 0.03 | 0.3 | shoot weight | Gast et al. 1978. |
| Technetium | NH4TcO4 | | oat | 10 | 0.3 | 1.2 | root & shoot weights | Gast et al. 1978. |
| Technetium | NH4TcO4 | | radish | 10 | 0.3 | 1.2 | shoot weight | Gast et al. 1978. |
| Technetium | NH4TcO4 | | corn | 10 | 3 | 5.8 | shoot weight | Gast et al. 1978. |
| Technetium | NH4TcO4 | | soybean | 10 | 5.8 | 7.8 | shoot weight | Gast et al. 1978. |
| Technetium | TcO4- | 5.5 | soybean | 14 | 5 | 20 | fresh weight seedlngs | Berlyn et al. 1980. |
| Tellurium | K2TeO3 | | wheat | 42 | | 2 LCT | root & shoot weights | Martin 1937b. |
| Thallium | TlCl3 | 4 | spruce | 7 | | 0.02 LCT | root length | Lamersdorf et al. 1991. |
| Thallium | $TlNO_3$ | | perrenial ryegrass | 21 | 0.1 | 0.5 | root and shoot weight and length | Al-Attar et al. 1988 |
| Thallium | Tl2SO4 | | lettuce | 3 | | 0.5 LCT | radicle length | Carlson et al. 1991. |
| Thallium | TlCl2 | | sunflower | | | 1 LCT | photosynthesis | Carlson et al. 1975 |
| Thallium | TlCl2 | | corn | | | 1 LCT | photosynthesis | Carlson et al. 1975. |
| Thallium | | | | | | 1 LCT | phytotoxic | Bowen 1979. |
| Thallium | Tl2SO4 | | turnip | 3 | 0.5 | 1 | radicle length | Carlson et al. 1991. |
| Thallium | Tl2SO4 | | wheat | 3 | 2.5 | 5 | radicle length | Carlson et al. 1991. |

**Table B.1 (continued)**

| Chemical | Form | pH | Plant species | DUR (D) | NOEC | LOEC | Growth parameter | Reference |
|---|---|---|---|---|---|---|---|---|
| Thallium | Tl2SO4 | | millet | 3 | 2.5 | 5 | radicle length | Carlson et al. 1991. |
| Thallium | Tl2SO4 | | radish | 3 | 2.5 | 5 | radicle length | Carlson et al. 1991. |
| Thallium | Tl2SO4 | | cabbage | 3 | 5 | 7.5 | radicle length | Carlson et al. 1991. |
| Tin | SnCl2 | | bush bean | 26 | 11.9 | 118.7 | shoot weight | Romney et al. 1975. |
| Titanium | TiCl3 | | bush beans | 21 | | 0.069 LCT | leaf weight | Wallace et al. 1977a. |
| Titanium | TiCl3 | 5 | cabbage | 55 | 0.4 | 4 | plant weight | Hara et al. 1976. |
| Uranium | UO2 | | soybean | 6 | 0.42 | 42 | seedling length | Murthy et al. 1984. |
| Vandium | NH4VO3 | 4.7 | lettuce | 45 | 0.1 | 0.2 | plant weight | Gil et al. 1995 |
| Vanadium | NH4VO3 | 5 | bush beans | 14 | .051 | 0.51 | root weight | Wallace 1979. |
| Vanadium | VOSO4 | | lettuce | 3 | 1 | 2.5 | radicle length | Carlson et al. 1991. |
| Vanadium | VOSO4 | | turnip | 3 | 1 | 2.5 | radicle length | Carlson et al. 1991. |
| Vanadium | VOSO4 | | cabbage | 3 | 1 | 2.5 | radicle length | Carlson et al. 1991. |
| Vanadium | VCl3 | 5 | cabbage | 55 | 0.4 | 4 | plant weight | Hara et al. 1976. |
| Vanadium | VOSO4 | | soybean | 33 | 3 | 6 | plant weight | Kaplan et al. 1990. |
| Vanadium | VOSO4 | | radish | 3 | 7.5 | 10 | radicle length | Carlson et al. 1991. |
| Vanadium | NH4VO3 | | pea | 14 | 10 | 20 | root & shoot weights | Nowakowski 1992. |
| Vanadium | VOSO4 | | millet | 3 | 50 | 60 | radicle length | Carlson et al. 1991. |
| Zinc | | 6 | clover | 46 | .082 | 0.41 | plant weight | Carroll & Loneragan 1968. |

Table B.1 (continued)

| Chemical | Form | pH | Plant species | DUR (D) | NOEC | LOEC | Growth parameter | Reference |
|---|---|---|---|---|---|---|---|---|
| Zinc | | 6 | barrel medic | 46 | .082 | 0.41 | plant weight | Carroll & Loneragan 1968. |
| Zinc | | 6 | lucerne | 46 | .082 | 0.41 | plant weight | Carroll & Loneragan 1968. |
| Zinc | ZnSO4 | 7 | ryegrass | 14 | | 1.85 LCT | root length | Wong and Bradshaw 1982. |
| Zinc | ZnSO4 | | chrysanthemum | 21 | 0.65 | 6.5 | stem weight | Patel et al. 1976. |
| Zinc | ZnSO4 | | bush beans | 16 | 0.65 | 6.5 | root & shoot weights | Wallace et al. 1977b. |
| Zinc | ZnCl2 | | broad bean | 3 | 8 | 10 | root length | Misra et al. 1994 |
| Zinc | ZnCl2 | | rice | 6 | | 26 EC50 | radicle weight | Wang 1994 |
| Aniline | | 7 | chinese cabbage | 21 | | 203.5 | root length | Feng et al. 1996 |
| Biphenyl | | | lettuce | 16 | | 2.1 EC50 | fresh weight shoot | Hulzebos et al. 1993 |
| 4-Bromoaniline | | 7 | chinese cabbage | 21 | | 102.2 | root length | Feng et al. 1996 |
| 4-Chloroaniline | | 7 | chinese cabbage | 21 | | 39.4 | root length | Feng et al. 1996 |
| 2-Chlorophenol | | 7 | chinese cabbage | 21 | | 58.3 | root length | Feng et al. 1996 |
| 4-Chlorophenol | | 7 | chinese cabbage | 21 | | 47.4 | root length | Feng et al. 1996 |
| 2-Cresol | | 7 | chinese cabbage | 21 | | 54.9 | root length | Feng et al. 1996 |
| 3,4-Dichloroaniline | | 7 | chinese cabbage | 21 | | 14.1 | root length | Feng et al. 1996 |
| 2,4-Dichlorophenol | | 7 | chinese cabbage | 21 | | 17.1 | root length | Feng et al. 1996 |
| Furan | | | lettuce | 16 | | 130 EC50 | fresh weight shoot | Hulzebos et al. 1993 |
| Heptane | | | lettuce | 16 | | 1.7 EC50 | fresh weight shoot | Hulzebos et al. 1993 |

**Table B.1 (continued)**

| Chemical | Form | pH | Plant species | DUR (D) | NOEC | LOEC | Growth parameter | Reference |
|---|---|---|---|---|---|---|---|---|
| Heptane | | | lettuce | 16 | | 47 EC50 | fresh weight shoot | Hulzebos et al. 1993 |
| Naphthalene | | | lettuce | 16 | | 13 EC50 | fresh weight shoot | Hulzebos et al. 1993 |
| 3-Nitroaniline | | 7 | chinese cabbage | 21 | | 69.2 | root length | Feng et al. 1996 |
| 4-Nitroaniline | | 7 | chinese cabbage | 21 | | 43.6 | root length | Feng et al. 1996 |
| Nitrobenzene | | | autumn olive | 2 | | 8 LCT | photosynthesis, transpiration | McFarlane et al. 1990. |
| 4-Nitrophenol | | 7 | chinese cabbage | 21 | | 12.3 | root length | Feng et al. 1996 |
| Pentachlorophenol | | | lettuce | 16 | | 0.03 EC50 | fresh weight shoot | Hulzebos et al. 1993 |
| Pentachlorophenol | | | lettuce | 16 | | 0.03 EC50 | fresh weight shoot | Hulzebos et al. 1993 |
| Phenol | | | lettuce | 16 | | 20 EC50 | fresh weight shoot | Hulzebos et al. 1993 |
| Phenol | | | lettuce | 16 | | 14 EC50 | fresh weight shoot | Hulzebos et al. 1993 |
| Phenol | | 7 | chinese cabbage | 21 | | 125.6 | root length | Feng et al. 1996 |
| Styrene | | | lettuce | 16 | | 18 EC50 | fresh weight shoot | Hulzebos et al. 1993 |
| Toluene | | | lettuce | 16 | | 16 EC50 | fresh weight shoot | Hulzebos et al. 1993 |
| 4-Toluidine | | 7 | chinese cabbage | 21 | | 102.2 | root length | Feng et al. 1996 |
| 2,4,6-Trichlorophenol | | 7 | chinese cabbage | 21 | | 12.7 | root length | Feng et al. 1996 |
| Ortho-xylene | | | lettuce | 16 | | 2 EC50 | fresh weight shoot | Hulzebos et al. 1993 |
| Xylene | | 6 | sugar beet | 2 | | 100 LCT | root length | Allen et al. 1961. |