Estimating Risk from Contaminants Contained in Agricultural Fertilizers

Draft Report

August 1999

Prepared by

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EPA Contract Number
68-W-98-0085

RTI Project Number
92U-7200-017

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List of Acronyms

AAPFCO	Association of American Plant Food Control Officials
AP-42	air pollutant emissions factors
BAFs	bioaccumulation factors
BASFs	bioaccumulation from sediment factors
BCFs	bioconcentration factors
Br	plant uptake values
CDD	chlorinated dibenzo-*p*-dioxins
CDFA	California Department of Food and Agriculture
CDFs	chlorinated dibenzofurans
CKD	cement kiln dust
CONUS	continental United States database
CSF	cancer slope factor
CV	coefficient of variance
DW	dry weight
EFH	Exposure Factors Handbook
EPA	Environmental Protection Agency
GIRAS	Geographic Information Retrieval and Analysis System
GIS	geographic information system
HEAST	Health Effects Assessment Summary Tables
HQ	hazard quotient
IEM	indirect exposure model
IEUBK	Integrated Exposure Uptake Biokinetic Model
IRIS	integrated Risk Information System
ISCST3	Industrial Source Complex Short-Term Version 3
ISMCS	International Station Meteorological Climate Summaries
K	potassium
K_2O	potassium oxide
K_ds	soil-water partitioning coefficients
LOAEL	lowest-observed-adverse-effect level
MF	modifying factor
MUID	map unit identification

List of Acronyms (continued)

N	nitrogen
NCDC	National Climate Data Center
NFCS	Nationwide Food Consumption Survey
NOAA	National Oceanic and Atmospheric Administration
NOAEL	no-observed-adverse-effect level
OAQPS	Office of Air Quality Planning and Standards
OIRM	Office of Information Resource Management
OPPTs	Office of Pollution Prevention and Toxics
ORD	Office of Research and Development
ORNL	Oak Ridge National Laboratory
OSW	Office of Solid Waste
OW	Office of Water
P	phosphorus
PCDDs	polychlorinated dibenzo-*p*-dioxins
PCDFs	polychlorinated dibenzofurans
ppb	parts per billion
ppm	parts per million
ppt	parts per thousand
RBC	risk-based concentration
Rcf	root concentration factor
RfD	reference dose
RTI	Research Triangle Institute
SAMSON	Solar and Meteorological Surface Observation Network
SCRAM	Support Center for Regulatory Air Models
SD_{SB}	sediment delivery ratio
SSLs	Superfund soil screening levels
STATSGO	State Soil Geographic database
STTN	Standards Technology Transfer Network
TCDD	tetrachlorodibenzodioxin
TEF	toxic equivalent factor
TEQ	toxic equivalency quotient
TFI	The Fertilizer Institute
UF	uncertainty factor
USAF	U.S. Air Force
USDA	U.S. Department of Agriculture
USLE	universal soil loss equation
USN	U.S. Navy
USSOILS	database of U.S. soil types
WW	wet weight

1.0 Executive Summary

1.1 Purpose

The U.S. Environmental Protection Agency's (EPA's) fertilizer risk assessment uses existing and available data to estimate potential risks posed to human health and the environment by contaminants in fertilizers. The primary purpose of the fertilizer risk assessment is to inform the Agency's decisions as to the need for federal regulatory action on fertilizer contaminants. In addition, EPA believes that the data and analytical methods used for this risk assessment may be useful to state regulatory agencies making decisions about the need for and nature of risk-based standards for fertilizers.

1.2 Approach

This risk assessment uses a probabilistic methodology to estimate the incremental increase in lifetime cancer risk and/or noncancer health effects associated with exposure to hazardous constituents contained in fertilizers and other agricultural soil amendments. The methodology used to assess the potential risk from hazardous constituents in fertilizers is adopted from EPA's assessment of risk from the use of cement kiln dust (CKD) as an agricultural liming agent. The CKD risk assessment methodology has been independently peer reviewed by the Cooperative State Research Education and Extension Service Technical Committee W-170 of the U.S. Department of Agriculture (USDA). For the fertilizer study, the risk assessment methodology has been revised to incorporate and address pertinent peer review comments and to more accurately and appropriately assess potential risks associated with hazardous constituents in fertilizer products.

Materials assessed include the most commonly used macronutrient fertilizers, which contain nitrogen, phosphorus, and potassium (NPK fertilizers); micronutrient (e.g., zinc) fertilizers; and soil amendments (i.e., materials applied to the land primarily to enhance soil characteristics rather than as plant food). The assessment evaluates the risks from 9 metals (cadmium, lead, arsenic, chromium, mercury, nickel, vanadium, copper, and zinc) and 17 dioxin congeners potentially contained in each of 13 fertilizer products. To address the range of climate conditions in areas where fertilizers are applied, this analysis assesses the use of fertilizers on different types of crops grown in 29 representative meteorological regions within the continental United States.

Information on fertilizer composition, contaminant concentration, and use pattern is provided in *Draft Final Report: Background Report on Fertilizer Use, Contaminants and Regulations* (U.S, EPA, 1998). Data on levels of dioxin concentrations in fertilizers used in this analysis are taken from the *Screening Survey for Metals and Dioxins in Fertilizers, Soil Amendments, and Soils in Washington State* (Rogowski and Golding, 1998).

Receptors evaluated in this analysis are farmers and their children who are exposed on a farm where the fertilizer product is applied at agronomically appropriate rates. Farmers and farm children are evaluated as the individuals within the general population who are most likely to be highly exposed to hazardous constituents in fertilizers. The exposure routes evaluated are

- Direct ingestion of fertilizer products during fertilizer application,
- Ingestion of soil amended with fertilizers,
- Inhalation of particles and vapors in the air during and after fertilizer spreading and tilling,
- Ingestion of plant and animal products produced on soil amended with these products, and
- Ingestion of home-caught fish from streams located adjacent to fertilizer-amended fields.

The groundwater exposure pathway (i.e., the ingestion of contaminated groundwater) was not evaluated for this analysis of risk from materials that are land applied which show that groundwater contamination is not likely to occur at levels of concern.

This analysis does not include a comprehensive evaluation of ecological risks. Ecological risks are evaluated, however, by comparing the concentrations of metals and dioxins predicted to be washed into streams located adjacent to farm fields to the EPA's ambient water quality criteria.

1.3 Findings

Of the large number of fertilizer products evaluated, only a few had contaminant levels high enough to potentially cause cancer risk or noncancer hazard of concern. Therefore, the results of this analysis indicate that, based on the data available, hazardous constituents in fertilizers generally do not pose harm to human health or the environment. The study indicates potential human health risks of concern from only arsenic and dioxin congeners found in select liming agents and micronutrient fertilizers. Generally, the potential risk from certain liming agents and micronutrient fertilizers can be attributed to a single product sample with a single high constituent concentration that far exceeds contaminant levels found in other similar fertilizer products. With these few exceptions, the contaminant levels found in the fertilizer products analyzed for this report are not expected to cause risks of concern, either through contamination of food products or through incidental ingestion of either the fertilizer product or of soil amended with fertilizer.

As previously noted, risks estimated in this risk assessment are for the farmer and the farm child, individuals within the general population who are most likely to be highly exposed to hazardous constituents in fertilizers. Farmers and farm children are assumed to consume a large portion of their food intake from exposed vegetables, exposed fruit, root vegetables, and beef and dairy products from home-grown sources amended with fertilizer products. These receptors also are assumed to ingest amended soil, to inhale vapors and particles from windblown emissions and emitted during the application of fertilizer products, and to ingest fertilizer products incidentally on the days that fertilizers are applied. The risks estimated using these high-exposure assumptions should reasonably demonstrate the limit for risk for all receptors. All other receptors (adult and child residents, recreational fishers, and home gardeners) are expected to have lower exposures through fewer pathways and, thus, lower risk than the farmer and his/her child.

Based on the ecological screening assessment, no exceedances of water quality criteria are projected.

1.4 Uncertainties

Uncertainty is inherent in the risk assessment process. It occurs because the risk assessment process is complex, and variability is inherent in the environment. Primary sources of uncertainty and their implications for this risk assessment are discussed in Section 8 of this document. They are summarized here.

Product characterization, which includes assumptions about fertilizer composition and use, is a primary source of uncertainty in this risk assessment. The data presented in this document incorporate a large number of fertilizer samples, and attempts have been made to include all available and acceptable data. Still, it must be noted that the data are limited and cannot be characterized as wholly representative of all fertilizer types. There is a wide range of metal concentrations in the fertilizers, as well as a wide range of application rates of fertilizers, which results in highly variable metal soil loadings from fertilizer application. EPA has attempted to address this variability by using all available data and a probabilistic risk assessment approach. Given the limited data available for some of the products assessed, however, products may exist outside the range of composition and application parameters considered by EPA for this assessment. Consequently, this approach is not adequate to fully characterize the variability in composition and use of fertilizer products.

The physical and chemical properties of soil are among the most important parameters affecting the fate and transport of metals and dioxins in agricultural environments. Relationships among many critical soil parameters are very complex and cannot be estimated by the simple systems used for fate and transport modeling in this risk assessment. Instead, complex interactions among soil parameters are addressed only indirectly in this risk assessment through the use of empirically derived soil-water distribution coefficients and soil-plant uptake factors for metals. Although his approach is likely to cover the range of complex soil and soil-plant interactions, much uncertainty remains in this area.

2.0 Introduction

2.1 Purpose

In 1997, the U.S. Environmental Protection Agency (EPA) initiated an effort to examine whether contaminants in fertilizers may be causing harmful effects and whether additional government actions to safeguard public health and the environment may be warranted. As part of that effort, EPA's Office of Solid Waste (OSW) undertook an assessment of the potential risks posed by heavy metals and other contaminants in fertilizers. This report presents the findings of that risk assessment. The risk assessment is based in large part on a study conducted by EPA's Office of Pollution Prevention and Toxics (OPPT), which assembled and synthesized available information on contaminants in fertilizers and soil amendments, fertilizer application rates, and how fertilizers are regulated in the United States and in other countries. The results of that study are presented in *Draft Final Report: Background Report on Fertilizer Use, Contaminants and Regulations* (U.S. EPA, 1998, referred to here as the OPPT report).

EPA's fertilizer risk assessment is intended primarily to estimate, based on existing and available data, the magnitude of potential risks to humans that may be posed by contaminants in fertilizers and, thus, to inform the Agency's decisions on the potential need for federal regulatory action on fertilizer contaminants. The results of the risk assessment also may assist the Agency in making certain general findings about the Resource Conservation and Recovery Act (RCRA) rule-making effort currently under development for hazardous waste-derived fertilizers. In addition, EPA believes that the data and analytical methods used for this risk assessment may be useful to state regulatory agencies making decisions about the need for and nature of risk-based standards for fertilizers.

2.2 Background

This report presents the risk assessment methodology used to estimate the incremental increase in lifetime risk from the use of fertilizers and other agricultural soil amendments. Materials assessed include the most commonly used macronutrient fertilizers, which contain nitrogen, phosphorus, and potassium (NPK fertilizers); micronutrient (e.g., zinc) fertilizers; and soil amendments (i.e., materials applied to the land primarily to enhance soil characteristics rather than as plant food).

The methodology used to assess the potential risk from fertilizers is adopted from EPA's assessment of the risk from the use of cement kiln dust (CKD) as an agricultural liming agent. EPA's OSW conducted an assessment of the risk to individuals from the agricultural use of CKD as part of the Agency's development of proposed regulations governing storage, management, and disposal of CKD. The CKD agricultural use risk assessment evaluated fate and transport of hazardous constituents (metals and dioxin) through air, soil, and surface water pathways. Receptor scenarios analyzed for the CKD analysis included the farmer, fisher, home gardener, and child of farmer exposed through both direct (e.g., soil ingestion) and indirect (i.e., food chain) routes of exposure. The CKD proposed rule is scheduled to be published in the *Federal Register* in summer 1999.

Although the methodology used to assess the risks from CKD is used as a framework for the fertilizer assessment, the fertilizer assessment has been adapted or altered as necessary to address use and composition differences between CKD and other types of soil amendments. Assumptions regarding hazardous constituent concentrations in fertilizers and soil amendments and agricultural application rates and frequencies are based on information provided in the OPPT report. In addition, the CKD risk assessment was submitted for peer review to the Cooperative State Research Education and Extension Service Technical Committee W-170 of the U.S. Department of Agriculture (USDA). A copy of the W-170 peer review report is provided in Appendix A.

A number of substantive recommendations made regarding the CKD assessment by the peer reviewers for that assessment are pertinent to the fertilizer assessment. These comments have been considered for the fertilizer assessment, and the risk assessment methodology has been revised to address them and to more accurately and appropriately assess potential risks associated with hazardous constituents in fertilizer products. Appendix B contains a report which describes the fertilizer-related issues raised by the CKD risk assessment peer reviewer panel and presents options and recommendations for revising the CKD methodology to assess the risks associated with hazardous constituents in fertilizer products.

2.3 Document Organization

Section 3, Analytical Framework—presents an overview of the risk analysis.

Section 4, Risk Assessment Scenario—discusses how risk assessment scenarios are established, including characterization of fertilizer products (i.e., definitions, patterns of use, application rates, constituent composition), geographic location, and associated parameters (i.e., meteorologic regions, agricultural land use, climate data, soil data, farm size, crop types, and plant uptake factors) and a description of receptors and exposure pathways.

Section 5, Estimating Exposure Point Concentrations—describes the methodology used to estimate exposure point concentrations. This section also identifies and describes the fate and transport and exposure models used in this risk assessment.

Section 6, Exposure and Toxicity Assessments—presents exposure assumptions used for incidental ingestion of fertilizers, ingestion of soil, ingestion of homegrown produce (vegetables, fruits, root crops, and so on), home-produced beef and dairy products, and home-caught fish. The effects of exposure duration, body weight, and inhalation rate also are addressed. This section also presents and discusses health benchmarks for metals and dioxin congeners.

Section 7, Risk Characterization—presents a summary of the results of this analysis and provides a characterization of the human health risks from metals and dioxins in fertilizer products. Ecological risk screening results also are presented in this section.

Section 8, Uncertainty—discusses the variability and uncertainty associated with this risk assessment.

Section 9, Comparison of Standards—compares EPA's fertilizer risk assessment with comparable standards and assessments. Both the state of California and Canada have undertaken efforts to identify and limit potential risks from the use of fertilizers. In addition, EPA regulates the use of sewage sludge applied to land. EPA's sewage sludge standards set risk-based concentration limits for metals in sewage sludge that are used to condition soil or fertilize crops. This section provides a brief summary of the scope and purpose of each of these efforts, describes the methodology used to derive standards, and identifies key similarities and differences between these efforts and the fertilizer assessment described in this document.

Section 10, References—contains a list of all citations in this document.

3.0 Risk Assessment Framework

This section presents an overview of the process used to estimate potential risks to human health from exposure to contaminants in fertilizers and other agricultural soil amendments.

3.1 Establishing Risk Assessment Scenarios

This risk assessment is designed to estimate the incremental increase in lifetime risk to farmers and their children who are exposed to metals and dioxin compounds contained in fertilizer products. Farmers and farm children are evaluated as the individuals within the general population who are most likely to be highly exposed to the hazardous constituents in fertilizers. The assessment evaluates both direct exposure to metals and dioxins during fertilizer application and indirect exposure to these compounds through ingestion of plant products produced on fertilized soil and animals fed fertilized produce. The analysis estimates concentrations for each metal and dioxin congener in soils, surface water, plant tissue (fruits, vegetables, grains, and forage), and animal tissue (fish and beef and dairy products) for each of the 13 fertilizer products. The analysis evaluates the use of fertilizers for five different categories of crops grown within 29 climate regions within the United States.

3.1.1 Characterization of Fertilizer Products—Composition and Use

3.1.1.1 Description of Fertilizer Products Analyzed. Information on fertilizer products (i.e., ingredients, levels of contaminants, use patterns) is taken from information provided in *Draft Final Report: Background Report on Fertilizer Use, Contaminants and Regulations* (U.S. EPA, 1998). This report documents metal concentrations in fertilizer products and application rates associated with those products. The products are grouped into three primary types of fertilizers: primary nutrients, liming agents, and micronutrients. Primary nutrients include products that contain nitrogen (N), phosphorus (P), and potassium (K) either singly or in combination (NPK). Liming agents are products intended to neutralize soil acidity. Micronutrient products are products used to supplement the needs of plants for certain metals, including boron, chlorine, cobalt, copper, iron, manganese, molybdenum, sodium, and zinc. Micronutrient products, in particular, may be derived or produced from hazardous waste. The U.S. Environmental Protection Agency (EPA) report on fertilizer characterization, however, does not provide information on which fertilizer products are derived from hazardous waste. Consequently, risks from hazardous waste-derived fertilizers cannot be characterized separately from nonwaste-derived products for this analysis.

The combinations of application rates and constituent concentrations reported in EPA's fertilizer characterization document are used to estimate the metal loading rates to the soil, which are the primary driving factors for risk in this assessment. According to the report, micronutrient fertilizers contain the highest concentrations of metals; however, the application rates reported for these products are very low. Primary nutrient fertilizers have relatively low metal concentrations and moderate application rates. Liming agents have moderate concentrations of metals but very high application rates.

Data on levels of dioxin concentrations in fertilizers used in this analysis are taken from *Screening Survey for Metals and Dioxins in Fertilizers, Soil Amendments, and Soils in Washington State* (Rogowski and Golding, 1998). This document presents sampling and analysis results for 51 fertilizer products for 17 dioxin congeners. Application rates for the fertilizers analyzed were not included in the Washington state report; therefore, application rates for corresponding product types from the EPA report are used to estimate loadings of dioxin to agricultural soils.

3.1.1.2 Geographic Location and Associated Parameters. The geographic location of fertilizer application determines many significant fate and transport factors in this risk analysis. Location-related parameters that most influence fate and transport of contaminants are climate condition and soil type. To address the range of climate conditions in areas where fertilizers are applied, this analysis assessed the use of fertilizers in 29 meteorological regions within the continental United States (CONUS). These 29 regions are considered to be representative of both the broad geographic climate regions that characterize CONUS and the more narrowly defined meteorological stations for which data are available throughout the United States. Climate parameters, such as annual rainfall, and meteorological parameters, such as annual average wind speed (used for air modeling), were assumed to be uniform throughout the climate region for this analysis. These data were obtained from the National Climate Data Center (NCDC). The analysis used the ranges of climate and meteorological data pertaining to a single site within the climate region. The parameters corresponding to the individual site were assumed to be representative of the parameters for the region.

Additional geographic information (e.g., land use type, soil conditions) for smaller geographic units corresponding to specific areas and locations within each of the 29 climate regions is available from geographic information system (GIS) databases. In a GIS, each of these smaller areas or “map units” has its own identification number so that location-specific data can be pulled from GIS databases using map unit identification numbers. For this analysis, only agricultural land was assessed. Areas within each climate region used for agriculture were identified based on data provided in the Geographic Information Retrieval and Analysis System (GIRAS), a GIS database developed and maintained by EPA, which contains land use information. Soil parameter data for each map unit were obtained from existing GIS databases (e.g., the State Soil Geographic [STATSGO] database) and integrated and varied in the analysis within each climate region. Integration of information maintained in GIS databases provides a means of addressing variations in climate and soil conditions as part of the risk analysis.

3.1.1.3 Crop Types. The type of crop to which fertilizer is applied is significant in determining how much of a contaminant is taken up in the crop. Key inputs necessary to estimate contaminant concentrations in plant tissue include rates of contaminant uptake into plants from soil and vapor and from deposition of particles onto plant surfaces. The agricultural census database maintained by the U.S. Department of Agriculture (USDA) indicates which crops are produced commercially in each county in the United States. For this analysis, the list of specific crops presented in the Agricultural Census was grouped into five categories: grains, forage, fruit, herbage, and roots. Plant uptake factors specific to each crop type are used to estimate the concentration of the contaminant in plant tissue as a function of concentrations in the soil. All crops are produced in all regions; however, predominant production for each crop occurs in specific geographic locations. Risk is estimated for all products applied to all crops in all areas.

3.1.2 Description of Receptors and Exposure Pathways

3.1.2.1 Receptors. The receptors in this risk analysis are farmers and their children who are exposed on a farm where the fertilizer product is applied as directed. The relevant exposure routes are

- Direct ingestion of the fertilizer product during fertilizer application,
- Ingestion of soil amended with fertilizers,
- Inhalation of particles and vapors in the air during and after fertilizer spreading and tilling,
- Ingestion of plant and animal products produced on soil amended with these products, and
- Ingestion of home-caught fish from streams located adjacent to fertilizer-amended fields.

The groundwater exposure pathway (i.e., ingestion of contaminated groundwater) was not evaluated for this assessment based on previous analyses of the risk from land-applied materials. These analyses include EPA’s assessment of risk from land treatment of petroleum industry waste for the Agency’s hazardous waste listing program, an assessment of risk from fertilizers conducted by the state of California, and EPA’s assessment of risk from the agricultural use of biosolids. The results of these analyses indicate that potential risks from groundwater pathways are expected to be low relative to those from nongroundwater pathways (e.g., ingestion of contaminated soil or food products). Based on the results of these analyses, EPA did not conduct a quantitative analysis of groundwater pathway risk from fertilizer use for this assessment.

This analysis does not include a comprehensive evaluation of ecological risks. Ecological risks are evaluated by comparing the concentrations of metals and dioxins predicted to be washed into streams located adjacent to farm fields to EPA’s ambient water quality criteria.

3.1.2.2 Exposure Pathways. Pathways evaluated in this risk analysis are presented below. All exposure pathways evaluated are assumed to occur as a result of recommended agronmonically appropriate use procedures for fertilizer products.

Table 3-1. Exposure Scenarios

Pathways	Adult Farmer	Child of Farmer
Inhalation Pathways		
Windblown emissions	✓	✓
Application and tilling	✓	✓
Ingestion Pathways		
Ingestion of product	✓	
Ingestion of soil	✓	✓
Ingestion of vegetables	✓	✓
Ingestion of fruits	✓	✓
Ingestion of root vegetables	✓	✓
Ingestion of beef and dairy products	✓	✓
Ingestion of home-caught fish	✓	✓

Product→human ingestion

Product→soil→human ingestion

Product→soil→air→human inhalation

Product→soil→air→plant→human ingestion (above-ground vegetable, fruit)

Product→soil→air→plant→cattle→human ingestion (beef and dairy through forage and silage)

Product→soil→plant→human ingestion (above-ground vegetable, fruit, root vegetable)

Product→soil→plant→cattle→human ingestion (beef and dairy through grain, forage, and silage)

Product→soil erosion→stream→fish→human ingestion

Product→soil→air→stream→fish→human ingestion

3.2 Estimating Exposure Point Concentration

3.2.1 Risk Assessment Method

This risk assessment uses a probabilistic methodology to estimate a distribution of lifetime risk to the individual farmer and farm child from 9 metals and 17 dioxin congeners in 13 fertilizer products applied to crops in 29 climate regions. Risks are estimated based on distributions of exposure point concentrations of each of the hazardous constituents in soil, surface water, plant tissue, and animal tissue combined with distributions of assumptions about the amount and rate of ingestion or other exposure to contaminated products. Commercially available software (Crystal Ball) was used to perform a Monte Carlo simulation.

Monte Carlo analysis is a statistical technique that calculates an individual risk value repeatedly using randomly selected inputs for each parameter in the exposure scenario. This methodology provides a means of quantifying variability and uncertainty in risk assessments by evaluating combinations of a range of possible parameters. Examples of variable parameters that are critical to an assessment of risk from fertilizers include concentrations of hazardous constituents, rates and frequencies of fertilizer application, and assumptions about food intake. Values selected for the input parameters are taken from a distribution of possible values for each parameter. Repetitive calculations using randomly selected combinations of input parameters generate a distribution of risk results from which risks representing the high end (e.g., 90th percentile) or central tendency (i.e., 50th percentile) can be determined. Although the simulation is internally complex, commercial software performs the calculations as a single operation, presenting a distribution of risk results associated with varying combinations of possible input parameters.

3.2.2 Fate and Transport Modeling

This risk analysis employs several key fate and transport models. A particle emissions model (AP-42) is used to estimate the rate of emission for particles from agricultural fields under various soil and climate conditions (U.S. EPA, 1995). EPA's Industrial Source Complex Short Term, Version 3 (ISCST3) is used to estimate the dispersion and deposition of vapors and particles emitted from agricultural fields (U.S. EPA, 1998). Soil partitioning is modeled using equations presented in a series of articles by Jury and colleagues (1983, 1984, 1990). The soil partitioning model is used to estimate the contaminant concentrations in soil after loss from soils as a result of degradation, volatilization, leaching, and rainwater runoff. The universal soil loss equation (USLE) is used to estimate soil erosion and transport of sediment from agricultural fields to nearby waterbodies (USDA, 1978). Finally, EPA's indirect exposure model (IEM) is used to estimate exposure point concentrations and individual risk by indirect or food chain pathways (U.S. EPA, 1993).

3.2.2.1 Air Modeling

3.2.2.1.1 ***Particle Emissions Model (AP-42)***. *EPA's Compilation of Air Pollutant Emission Factors* (U.S. EPA, 1985b) (referred to as AP-42) presents a series of equations used to estimate the rate of emission for particles under various conditions. In this analysis, equations are used to estimate emission rates for annual average windblown emissions and for intermittent emissions due to fertilizer application and tilling operations. These emission rates are summed to estimate a total annual emission rate for particles. This model used soil and climate parameters in the equations, and the results are specific for each climate region.

3.2.2.1.2 ***Air Dispersion and Deposition Model (ISCST3)***. Air dispersion and deposition modeling is used to estimate the initial fate and transport of vapor and particle emissions in the environment. Air dispersion modeling is conducted with ISCST3 (U.S. EPA, 1998). The ISCST3 model is used to estimate the air concentration of vapors, the wet deposition of vapors, the air concentration of particles, the wet deposition of particles, and the dry deposition of particles. These outputs are used to estimate risk through direct inhalation and through deposition of contaminants onto plant surfaces and into nearby streams.

3.2.2.2 Soil Modeling

3.2.2.2.1 ***Soil Partitioning Model***. The soil partitioning model is used to simulate the application of metals and dioxins to the agricultural fields and to estimate the loss of constituents that occurred over time through leaching, volatilization, runoff, and biodegradation. Equations used in this model are based on equations described by Jury et al. (1983, 1984, 1990). Data used in these equations to estimate the fate and transport of constituents in soil include initial product constituent concentrations; application rates; application frequencies; periods of application; soil and climate parameters; and constituent-specific physical and chemical properties, such as Henry's law constants and soil-water partitioning coefficients (K_ds). This model is used to estimate the soil concentration and the emission rate for volatile constituents at annual intervals during and after fertilizer application.

3.2.2.3 Surface Water Modeling

3.2.2.3.1 ***Universal Soil Loss Equation***. The USLE is used to estimate soil erosion and overland transport of sediment from agricultural fields across intervening areas to nearby waterbodies using a distance-based sediment delivery ratio (USDA, 1978). To preserve mass balance within the setting, the sediment not reaching the waterbody is assumed to be deposited evenly over the area intervening between the farm field and the nearby stream.

3.2.2.4 Food Chain Modeling

3.2.2.4.1 ***Indirect Exposure Model***. The indirect exposure model is used to estimate the fate and transport of constituents through the environment and into the food chain to produce estimates of human health risk. Risks to the farm family can occur through ingestion of plants grown on amended soil and/or through ingestion of beef and dairy products from animals raised on fertilized crops. The indirect exposure model is used to estimate exposure point concentrations in plant, animal, and fish tissue by using constituent- specific food chain biotransfer factors.

A distribution of plant biouptake factors for metals was developed specifically for this analysis. A large number of literature sources were reviewed to identify the range of soil-plant uptake factors that adequately represent the physical and chemical interactions that occur in fertilizer-amended soil and that correspond to the specific crop types assessed. For beef and dairy products, empirically derived food chain transfer factors were used to estimate the concentrations of metals and dioxins in animal tissue. For fish, bioconcentration factors are used to estimate the concentrations of metals in fish tissue based on the metal concentration in the water column. Fish sediment accumulation factors are used to estimate the concentrations of dioxins in fish tissue based on the concentrations in the sediment.

3.3 Exposure and Toxicity Assessments

The estimated exposure point concentrations in soil, plants, and animal products are combined with exposure factors (e.g., exposure duration, ingestion rates) and toxicity benchmarks to estimate human health risk. The exposure factors used in this risk assessment are distributions provided in the *Exposure Factors Handbook* (U.S. EPA, 1997a, 1997b, 1997c). Toxicity assessments are performed differently for carcinogens and noncarcinogens. For carcinogens, EPA calculates the probability of getting cancer from a particular exposure level using a cancer slope factor. For noncarcinogens, the Agency calculates the ratio of the exposure level to an allowable reference dose to determine a hazard quotient (HQ).

Health benchmark values used for metals in this analysis were taken from the Integrated Risk Information System (IRIS) database or the Health Effects Assessment Summary Tables (HEAST) (U.S. EPA, 1997f). The health benchmark for dioxin congeners was obtained from *Estimating Exposure to Dioxin-Like Compounds* (U.S. EPA, 1994a). No health benchmark was available for lead. Instead, adverse effects from lead are defined in terms of blood lead levels. To estimate blood lead levels, exposure point concentrations of lead were used as inputs to the Integrated Exposure Uptake Biokinetic (IEUBK) model for lead, which calculates blood lead level concentrations. These concentrations are then compared to a benchmark of 10 µg/dL.

3.4 Characterizing Risk

The Monte Carlo analysis conducted for this assessment generates 1,000 risk estimates (cancer probabilities or HQs) by exposure pathway for each constituent and each combination of the 13 fertilizer products and the 29 climate regions evaluated. These estimates are used to develop a distribution of risk and HQs for each of these combinations, which could then be evaluated to identify potential human health risks associated with fertilizer use. EPA's hazardous waste program generally defines levels of concern for carcinogens as risks of 1×10^{-5} (1 in 100,000) at the upper end of the risk distribution (e.g., 90th or 95th percentile). An HQ of 1 or greater at the upper end of the distribution is generally used to indicate noncancerous effects of concern. The quantitative results of this assessment are summarized in Section 7.0. The results of this analysis indicate that fertilizers generally do not pose harm to human health or the environment.

4.0 Establishing Risk Assessment Scenarios

This analysis assesses the risks to human health from use of fertilizers, micronutrients, and other agricultural soil amendments. The assessment evaluates potential risks associated with 13 agricultural products that contain measured concentrations of metals and dioxin congeners and are applied to agricultural fields and home gardens at recommended application rates and frequencies. The fields and gardens are assumed to be located within the conterminous United States. This section identifies and provides information on data the U.S. Environmental Protection Agency (EPA) used to conduct the risk assessment. It also identifies and describes the exposure pathways assessed in this analysis.

4.1 Characterization of Fertilizer Products

This section first summarizes information on characterization and use of fertilizers and soil amendments and then provides specific information on the composition and application of individual primary nutrient, secondary nutrient, and micronutrient fertilizers and liming materials considered in this analysis. The data presented in this section are taken from *Draft Final Report: Background Report on Fertilizer Use, Contaminants and Regulations*, published by the EPA's Office of Pollution Prevention and Toxics (OPPT) (U.S. EPA, 1998).

It is important to acknowledge the limitations of the data used in this analysis. The data presented in this document incorporate a large number of fertilizer samples, and attempts have been made to include all available and acceptable data. Still, it must be noted that the data are limited and cannot be characterized as wholly representative of all fertilizer types. There is a wide range of metal concentrations in the fertilizers as well as a wide range of application rates, which result in highly variable metal soil loadings from fertilizer application. Again, although EPA has attempted to address this variability by using all available data and probabilistic assessment methodology, products may exist that are outside the range of composition and application parameters considered by EPA for this assessment.

4.1.1 Definition of Fertilizers and Soil Amendments

A *fertilizer* is defined by the Association of American Plant Food Control Officials (AAPFCO) as "any substance containing one or more recognized plant nutrient(s) which is used for its plant nutrient content and which is designed for use or claimed to have value in promoting plant growth" (AAPFCO, 1997a). A *fertilizer material* is a fertilizer that either

(a) Contains important quantities of no more than one of the primary plant nutrients: nitrogen (N), phosphorus (P), and potassium (K); or

(b) has 85% or more of its plant nutrient content present in the form of a single chemical compound; or

(c) is derived from a plant or animal residue or by-product or natural material deposit which has been processed in such a way that its content of plant nutrients has not been materially changed except by purification and concentration (AAPFCO, 1997b).

Primary nutrients in fertilizers are nitrogen (N), available phosphate (P_2O_5), and soluble potash (K_20). Fertilizers are developed to contain these individual nutrients or a combination of them (multiple-nutrient fertilizers). Secondary nutrients and micronutrients are defined by AAPFCO as “those other than the primary nutrients that are essential for the normal growth of plants and that may need to be added to the growth medium.” Calcium, magnesium, and sulfur are considered to be secondary nutrients, whereas micronutrients include boron, chlorine, cobalt, copper, iron, manganese, molybdenum, sodium, and zinc. A liming material is defined as “a product whose calcium and magnesium compounds are capable of neutralizing soil acidity” (AAPFCO, 1997b).

4.1.2 Consumption Patterns in the United States

According to the OPPT report, more than 54 million tons (110 billion lb) of commercial fertilizers and liming materials were purchased commercially for use in the United States in the year ending June 30, 1996. Primary nutrients (N, P, K) accounted for 91 percent of this total, liming material accounted for about 4 percent, and organic fertilizers for 1 percent. Approximately 5 percent was due to secondary nutrient fertilizers (calcium, magnesium, sulfur) and micronutrients.

Fertilizer consumption was reported for nine main regions: New England, Middle Atlantic, South Atlantic, East North Central, West North Central, East South Central, West South Central, Mountain, and Pacific. The three regions with the highest total fertilizer consumption are the West North Central region (12,905,624 tons), the East North Central region (10,696,555 tons), and the South Atlantic region (8,209,554 tons).

States with the highest fertilizer consumption are the agricultural states in the Corn Belt and California. Florida (1.6 million tons) and Texas (1.6 million tons) consume the most multiple-nutrient fertilizers, whereas Illinois consumes the most single-nutrient nitrogen, phosphate, and potash fertilizers (1.9, 0.8, and 1.0 million tons, respectively). North Carolina consumes the most liming materials (0.9 million tons), whereas California consumes most of the secondary nutrient and micronutrient fertilizers (1.6 million tons). Individual states that consume more than 2 million tons of fertilizer include Florida, Minnesota, Ohio, Nebraska, North Carolina, Texas, Iowa, Illinois, and California.

Fertilizer consumption also is presented by major crop type in the OPPT document. Corn is the field crop with the most acres planted (70 million) and the highest levels of nitrogen, phosphate, and potash fertilizers applied to it (9, 3, and 4 billion lb, respectively). Ninety-nine percent of the tobacco crop (0.4 million acres) and more than 90 percent of the potato crop (0.8

million acres) are fertilized with nitrogen, phosphate, and potash fertilizers. Less than 30 percent of the soybean crop (50 million acres) receives applications of these primary nutrients.

4.1.3 Application Rates

The application rates for nitrogen, phosphate, and potash fertilizers presented in the OPPT document are taken from the U.S. Department of Agriculture's (USDA's) National Agricultural Statistics Service database. Application rates for secondary nutrients, micronutrients, lime, and gypsum are derived from interviews with experts in the area, including leading scientists with the agricultural extension services in seven states, and from information published by agricultural extension services on the Internet for eight states. Because of the variability in application rates of fertilizers, the rates in the OPPT document cover a range of potential values. Only selected percentiles from the distribution of application rates are presented in the OPPT document. The application rates reported in the OPPT document are given as the application rate per unit active ingredient. The 50th percentile is presented as the average application rate, the 85th percentile as the high application rate, and the 95th percentile as the maximum application rate. For this risk assessment, the selected percentiles presented in the document were used to develop a distribution of application rates. It is assumed that all fertilizer products are applied annually. Table 4-1 shows the average, high, and maximum application rates of fertilizers, as presented in the OPPT document. The distributions of application rates are developed based on a normal distribution, and the percentiles in this table are presented in Appendix J.

Application rates of fertilizers affect the metal soil loadings resulting from fertilizer application. The OPPT document also includes the percentage of the active ingredient in each product and the measured concentration of each metal in the product so that comparable loading rates for metals can be developed for products based on the application of a unit active ingredient. For example, although high levels of metals are often in the micronutrient fertilizers, the low application rates of these fertilizers do not necessarily lead to high metal contents in the soil. Additionally, the percentage of the fertilizer sample that is composed of the fertilizer's active ingredient varies. For example, the percentage of P_2O_5 in the phosphate samples ranges from 53 to 15 percent. This means that more of the low-percentage (15 percent) phosphate fertilizers must be applied to result in equal addition of a unit of P_2O_5 application than the higher percentage (53 percent) phosphate product. All application rates reported in the OPPT document are used in combination with the percentage of the active ingredient to estimate metal loading rates in this analysis. Fertilizer is assumed to be applied over a period of 100 years for this analysis.

4.1.4 Constituent Composition

4.1.4.1 **<u>Metals</u>**. Some of the raw materials used in fertilizers contribute to the metal content of the fertilizers. These raw materials include rock phosphates (for NPK fertilizers), recycled industrial waste with a high zinc content (for zinc micronutrient fertilizers), and municipal sewage sludge (for organic fertilizers). In general, on a mass concentration basis (mg/kg), the primary fertilizers (nitrogen, phosphate, and potash fertilizers) are lower in metal content (cadmium, lead, nickel, and copper) than the zinc micronutrient fertilizers.

Table 4-1. Application Rates (lb/acre) per Unit Active Ingredient Used in Calculation of Metal Addition to Soil for Field Crops, Vegetables, and Fruits

Fertilizer Type (Active Ingredient)	50th Percentile (Average) (lb/acre)	85th Percentile (High) (lb/acre)	95th Percentile (Maximum) (lb/acre)
Phosphate (P_2O_5)	84	173	252
NPK applied for phosphorus (P)	84	173	252
NPK applied for nitrogen (N)	124	206	414
Potash (K_20)	103	177	534
Sulfur (nutrient)	20	40	60
Sulfur (pH)	800	2,000	2,500
Lime[1] ($CaCO_3$)	4,000	8,000	15,000
Gypsum	2,000	4,000	8,000
Iron	10	20	30
Boron	2	3	4
Manganese	4	10	18
Zinc	5	10	20
Micronutrient mixes	7	NA	NA

[1]Lime is typically applied every 2-3 years but the application rates have been normalized based on $CaCO_3$ content to provide annual application rates. Additionally, the distribution includes a sample which contains only 7.6% $CaCO_3$. Up to 10 times as much of this product must be used to achieve the same liming effect as most other products.
NA = Not available.
Source: U.S. EPA (1998).

The metals considered in this analysis include cadmium, lead, arsenic, chromium, mercury, nickel, vanadium, copper, and zinc. Although additional metals are known to be present in fertilizers, this risk assessment is limited to data available in the OPPT document. Note that in the OPPT document the number of metals analyzed in each fertilizer product varied from one to the entire suite of nine. The limitations on analytical data available for several metals in a number of fertilizer products increase the uncertainty surrounding this analysis. The ranges of metal concentrations measured in different fertilizers are shown in Table 4-2. The application rates discussed in the previous section (Table 4-1), along with the concentration of metals in the fertilizers (Table 4-2), are used to calculate metal additions to the soil (mg/kg) from use of the various fertilizer products. Detailed data on the metal concentrations in individual fertilizers and fertilizer application rate distributions are provided in Appendix J.

Table 4-2. Metal Concentrations in Fertilizer Products (mg/kg)

Product	As	Cd	Cr	Cu	Pb	Hg	Ni	Vn	Zinc
Phosphate (P_2O_3)	11.3[1] (61)[2] 0.5-20.5[3]	65 (57) 0.15-250	173.3 (27) 63-896	56.6 (58) 0.2 -1,170	12.2 (49) 1-200	0.10 (5) 0.003-0.2	27.5 (34) 0.5-151	216 (8) 48.7-721	240.2 (29) 31.3-1,550
NPK for phosphorus (P)	12.8 (84) 0.05-155	30.6 (85) 0.03-47	83.9 (60) 4.3-616	31.4 (88) 0.44-700	216.5 (85) 0.1-5,425	0.07 (14) 0.003-0.2	28.5 (69) 0.5-195	165.7 (14) 25-396	233.6 (67) 1-2,193
NPK for nitrogen (N)	5.3 (49) 0.04-13.2	5.0 (46) 0.03-47	50.6 (41) 0.05-201	41.3 (47) 0.14-544	31.8 (49) 0.2-422	0.2 (7) 0.11-0.4	11.8 (43) 0.1-85.7	64.8 (42) 0.05-163	204.5 (38) 0.2-4,442
Potash (K_2O)	0.3 (17) 0.05-1.5	NA	0.5 (14) 0.05-2.75	1.0 (43) 0.05-5	NA	0.1 (16) 0.003-0.2	1.4- (41) 0.05-4.4	1.2 (16) 0.05-9	1.6- (39) 0.19-8.75
Sulfur (nutrient)	5.0 (9) 0.1-19	36.6 (4) 0.03-145	37.9 (6) 0.05-214	24.3 (9) 0.04-109	5.4 (6) 0.2-15	0.1 (3) 0.01-0.40	48.9 (4) 0.1-195	99.1 (4) 0.046-396	384.8 (4) 0.21-1,480
Sulfur (pH)	7.8 (5) 0.1-19	NA	NA	40.4 (5) 2-109	6.4 (2) 4-8.7	NA	NA	NA	NA
Lime ($CaCO_3$)	14.6 (10) 1-48	2.5 (10) 0.1-8.1	21.2 (7) 1.25-73	42.0 (9) 2.3-158	44.5 (10) 0.7-150	0.1 (8) 0.01-0.41	7.9 (8) 1.4-23	14.0 (8) 1-49	353.0 (7) 7.7-1770
Gypsum	4.5 (4) 3-8.5	1.7 (2) 0.8-2.5	1.4 (1)	23.7 (4) 7.2-42	4.6 (4) 1.5-11	0.011 (1)	3.0 (1)	33.9 (4) 1.4-50	53.8 (1)

Table 4-2. (continued)

Product	As	Cd	Cr	Cu	Pb	Hg	Ni	Vn	Zinc
Iron	1,662.3 (3) 2.5-4,950	177.0 (2) 20.5-333.5	NA	666.7 (3) 40-1,750	7,134.7 (3) 29-18,750	NA	NA	NA	NA
Boron	530.5 (2) 21-1,040	0.75 (1)	1.3 (1)	8.1 (1)	5.5 (1)	0.2 (1)	2.5 (1)	16.9 (1)	6.0 (1)
Manganese	7.8 (2) 0.5-15	2.3 (2) 1.5-3	10.0 (1)	11.3 (2) 1.5-21	27.5 (2) 5- 50	0.01 (1)	50 (1)	1.5 (1)	60.8 (1)
Zinc	20 (4) 0.5-45.5	398 (22) 2 - 2,165	338.9 (2) 97.8-580	1101 (4) 3-2050	10,013 (58) 13-52,000	3.36 (1)	890 (11) 10-8,950	20.75 (2) 0.5-41	NA
Micronutrient mixes	41.9 (2) 0.85-83	27.9 (2) .85-55	230 (2) 3.1-457	29,650 (2) 19,400-39,900	1,798 (2) 5.5-3,590	0.1 (2) 0.03-0.226	12.5 (2) 4-21	16.8 (2) 0.5-33	77,300 (2) 60,300-94,300

NA = Not available.

[1] Mean.

[2] (*n*) = Number of samples.

[3] Range.

The OPPT document summarizes expected loadings of metals associated with various types of fertilizers as follows:

> Application of zinc fertilizers at the maximum application rate results in soil additions of less than 0.1 kg/hectare of all metals except for lead (0.884 kg/ha). Phosphate products at the maximum application rate also result in metal addition to the soil of less than <0.1 kg/ha for all metals except chromium (0.1 kg/ha), vanadium (0.173 kg/ha), and zinc (0.150 kg/ha). NPK fertilizers applied for N content and applied at the maximum rate contribute 0.10 kg/ha/year of lead to the soil. Boron and K_2O fertilizers contribute extremely low levels of contaminants, generally <0.001 kg/ha/year at the maximum application rate, with the exception of 0.023 kg/ha/year of arsenic from boron fertilizers. Iron fertilizers contribute almost 0.5 kg/ha/year of arsenic and 1.6 kg/ha/year of lead to the soil when applied at the maximum rate. The manganese fertilizers contribute very low levels of contaminants, with the highest level contributed by the zinc in the manganese fertilizers at 0.004 kg/ha/year at the maximum application rate. Adding sulfur to the soil as a nutrient adds 0.18 kg/ha of zinc to the soil; adding sulfur for pH adjustment adds 0.11 kg/ha of copper to the soil each year at the maximum application rate. Average additions of zinc and vanadium (0.48 and 0.30 kg/ha, respectively) are the highest metal additions from gypsum applications. Zinc, lead and copper (at 6.6, 0.69, and 0.6 kg/a, respectively) are the metals added in highest quantities with liming agents (*Draft Final Report: Background Report on Fertilizer Use, Contaminants and Regulations*, U.S. EPA, 1998).

4.1.4.2 Dioxins. The Washington State Fertilizer Regulation Act of 1998 required the Washington State Department of Ecology to determine levels of heavy metals and dioxins in fertilizers, soil amendments, and soil. The resulting study analyzed both fertilizer products and background soil. The results are presented in *Preliminary Screening Survey for Metals and Dioxins in Fertilizers, Soil Amendments, and Soils in Washington State* (Rogowski and Golding, 1998). Because the OPPT document does not provide data for dioxins in fertilizer products, the Washington state report is the source for this information.

Dioxins, polychlorinated dibenzo-*p*-dioxins (PCDDs), and polychlorinated dibenzofurans (PCDFs) have been detected in fertilizers and soil amendments. Dioxins are unintended by-products formed during the combustion of organic compounds in the presence of chloride. The production of certain chlorinated organic products also produces dioxins as contaminants, as does chlorine bleaching of wood pulp. Dioxins have no commercial or domestic applications and are not intentionally produced, except for small quantities used in research.

Washington state sampled and analyzed 51 fertilizer products, including bulk agricultural fertilizers, home-use fertilizers, agricultural micronutrient products, and a soil amendment, for 17 dioxin congeners. The results of these analyses were reported using three methods for dealing with nondetected congeners. The first method assumed that if the congener was not detected, the concentration of that congener was zero (ND=0). The second method assumed that if the congener was not detected, the concentration was one-half the detection limit (ND=½ DL). The third method assumed that if the congener was not detected, the concentration was equal to the detection limit (ND=DL). Dioxin congeners are assumed to occur as a complex mixture of constituents; thus, for this risk analysis, the second method of handling nondetected congeners was used (i.e., if the congener was not detected, the concentration was set at one-half the detection limit [ND=½ DL]). This method was used only for those fertilizer products for which dioxins were detected in at least one sample. Fertilizers for which no dioxin congeners were detected in any sample are not included in this assessment.

According to the report, most fertilizer products analyzed showed nondetectable or extremely low levels of dioxin congeners. Some fertilizers, however, contained higher levels of dioxin congeners. Two micronutrient fertilizers had greater than 140 ppt of dioxin congeners, and one micronutrient exceeded 50 ppt. These three micronutrient fertilizers are believed to be derived from steel mill flue dust. Table 4-3 shows the fertilizers that were evaluated for potential dioxin risk and the concentrations of dioxin congeners in each of the fertilizers evaluated. Only those fertilizers identified in the Washington state report that might be applied to food crops were evaluated for this assessment. For example, Shultz Orchid Food is not evaluated in this risk assessment.

4.1.5 Characterization of Individual Fertilizers

This section provides more detailed information on individual primary nutrient, secondary nutrient, and micronutrient fertilizers and liming materials and their use patterns in the United States. This risk assessment focuses on four primary nutrient fertilizers (phosphate, NPK for phosphorus, NPK for nitrogen, and potash), four secondary nutrient fertilizers (sulfur as a fertilizer, sulfur as a pH adjustor, liming materials, and gypsum products), and five micronutrient fertilizers (zinc, manganese, boron, iron, and a mixed micronutrient).

4.1.5.1 Primary Nutrient Fertilizers.

4.1.5.1.1 ***Phosphate Fertilizers***. Phosphate is a primary nutrient whose content in fertilizers is measured by the available phosphorus oxide (P_20_5). Examples of phosphate fertilizers are calcium phosphates, ammonium phosphates, polyphosphates, and superphosphates. In 1996, approximately 7,204,054 tons of single-nutrient phosphate fertilizers were consumed in the United States, corresponding to 12 percent of the total fertilizer consumption. The two regions with the highest phosphate fertilizer consumption are the West North Central (2,827,389 tons) and East North Central (1,864,977 tons) regions. A review of fertilizer consumption within individual states indicates that Illinois (832,904 tons) and Iowa (647,541 tons) consume the largest amount of phosphate fertilizers.

Potatoes have the highest application rates of phosphate fertilizers (173 lb/acre), but because less than 1 million acres are planted, potatoes do not necessarily use the greatest quantity of phosphate fertilizers. The crop with the largest number of acres planted (70 million acres) is corn. At an application rate of 57 lb/acre of phosphate, corn uses the greatest quantity of phosphate fertilizers. Potatoes and corn are both classified as field crops. Vegetable crops with the highest application rates of phosphate fertilizers are cucumbers in North Carolina, bell peppers in California, and head lettuce in Arizona.

Table 4-3. Concentrations of Dioxin Congeners in Fertilizer Products Assessed in this Risk Analysis (ppt)

Fertilizer Product	2,3,7,8-TCDD	1,2,3,7,8-PCDD	1,2,3,4,7,8-HxCDD	1,2,3,6,7,8-HxCDD	1,2,3,7,8,9HxCDD	1,2,3,4,6,7,8-HpCDD	OCDD	2,3,7,8-TCDF	1,2,3,7,8-PCDF	2,3,4,7,8-PCDF	1,2,3,4,7,8-HxCDF	1,2,3,6,7,8-HxCDF	2,3,4,6,7,8-HxCDF	1,2,3,7,8,9-HxCDF	1,2,3,4,6,7,8-HpCDF	1,2,3,4,7,8,9-HpCDF	OCDF
Iron fertilizer (2)[1]	0.25 - 0.50	0.58 - 0.34	0.47-0.30	0.49-0.35	0.75-0.55	0.80-0.55	**2.9-2.12**	0.18-0.21	0.23-0.23	0.29-0.25	0.32-0.35	0.22-0.21	0.55-0.35	0.38-0.43	0.70-0.31	0.49-0.40	1.00-0.80
Liming agents (2)	**0.62-32.**	**2.9-15**	**2.6** **20**	**5.5** **40**	**3.7** **28**	**14** **160**	**15** **99**	**3.3** **17**	**2.9** 5.5	**5-20**	**2.8** **11**	**2.3** **7.1**	**3.4** **5.8**	**1.2** 0.7	1.95 **9.3**	1.4 **3.7**	**4.3** 1.4
Magnesium (1)	0.13	0.19	0.17	0.16	0.17	**0.36**	**1.3**	0.07	0.12	0.18	0.15	0.21	0.30	0.18	0.18	0.14	**0.68**
Phosphate (1)	0.16	0.12	0.22	0.23	0.26	0.33	**1.4**	0.18	0.09	0.09	**0.15**	0.14	**0.38**	0.16	0.34	0.43	0.28
Potash (1)	0.26	0.28	0.44	0.38	0.35	0.55	1.55	**0.18**	0.12	0.15	**0.23**	0.26	0.28	0.31	0.22	0.60	0.75
Zinc Micronutrients (12)	**(0.02-16)** ND=4[3]	**(0.06-130)** ND=5	**(0.08-130)** ND=6	**(0.13-400)** ND=4	**(0.13-660)** ND=4	**(0.28-1,500)** ND=4	**(0.30-780)** ND=2	**(0.11-410)** ND=3	**(0.16-235)** ND=5	**(0.17-740)** ND=5	**(0.18-850)** ND=4	**(0.14-420)** ND=4	**(0.2-410)** ND=2	**(0.07-62)** ND=6	**(0.23-1,000)** ND=4	**(0.17-360)** ND=4	**(0.30-780)** ND=4

Source: Rogowski and Golding (1998).

[1] Number of samples.

[2] Bolded values are measured or estimated (J) values. Nonbolded values are nondetects for which half the detection limit was used.

[3] Number of nondetects for which half the detection limit was used.

ND = Nondetect.

Phosphate fertilizers are known to contain varying levels of heavy metals such as cadmium, lead, nickel, and chromium (Charter et al., 1993; Mortvedt, 1987). These metals may originate in the phosphate rock (Kpomblekou-A and Tabatabai, 1994; Mortvedt and Giordano, 1977), and much of the cadmium, and other metals, remains with the phosphate during processing (Wakefield, 1980).

4.1.5.1.2 ***Potash Fertilizers***. Potassium oxide (K_2O), also termed potash, is a primary nutrient of plants. Examples of potash fertilizers are potassium chloride, potassium sulfate, potassium nitrate, and potassium thiosulfate. Approximately 5,988,338 tons of potash fertilizers were applied in 1996 in the United States, corresponding to 10 percent of the total fertilizer consumption. The regions with the highest consumption of potash fertilizers are the East North Central (2,524,402 tons) and West North Central (1,739,704 tons) regions. Among individual states, Illinois (979,455 tons) and Iowa (699,879 tons) consume the largest amount of potash fertilizers.

Tobacco fields have the highest application rates of potash fertilizers (203 lb/acre), but because less than 1 million acres of tobacco are planted, tobacco does not necessarily use the greatest amount of potash. Corn, with a potash application rate of 79 lb/acre for 70 million acres, uses the greatest quantity of potash (U.S. EPA, 1998). Vegetable crops with the highest application rates of potash fertilizers are fresh tomatoes, celery, and bell peppers in Florida.

4.1.5.1.3 ***Nitrogen Fertilizers***. Single-nutrient nitrogen fertilizers are described but not included in this analysis because no data are available for metal concentrations in them. Multinutrient fertilizers (NPK) applied for nitrogen are considered here, however. Nitrogen is a primary nutrient that is an essential element for plant growth. The nitrogen content in fertilizers indicates the amount of N available for plant growth. Examples of nitrogen fertilizers are nitrates, ammonium salts, liquid ammonium, urea, and natural organics. Approximately 23,412,475 tons of primary nitrogen fertilizers were consumed in the United States in 1996. The regions with the highest nitrogen fertilizer usage are the West North Central (7,547,376 tons) and East North Central (4,568,739 tons) regions. An analysis of fertilizer consumption for individual states shows that Illinois (1,920,268 tons) and Iowa (1,819,846 tons) consume the largest amount of nitrogen fertilizers.

Potato fields have the highest application rates for nitrogen fertilizers (195 lb/acre), but because less than 1 million acres of potatoes are planted, potatoes do not use the most nitrogen fertilizers. Again, corn, with a nitrogen application rate of 133 lb/acre for 70 million acres, uses the greatest quantity of nitrogen fertilizers. Vegetable and fruit crops with the highest application rates for nitrogen fertilizers are watermelons and lettuce.

4.1.5.1.5 ***NPK Fertilizers Applied for Phosphate or Nitrogen***. NPK fertilizers are multiple-nutrient, primary fertilizers that contain any combination of nitrogen, phosphorus, and potassium (NPK, NP, NK, or PK). Approximately 19,049,707 tons of these fertilizers were consumed in the United States in 1996, corresponding to 31 percent of the total fertilizer consumption. Multiple-nutrient fertilizers can be applied for either phosphate or nitrogen use. This analysis models these two types of fertilizer applications separately.

The regions with the highest multiple-nutrient fertilizer usage are the South Atlantic (4,428,838 tons), West North Central (3,409,920 tons), and East North Central (3,183,297 tons) regions. Among individual states, Texas (1,622,103 tons) and Florida (1,562,946 tons) consume the largest amount of multiple-nutrient fertilizers.

4.1.5.2 Secondary Nutrient Fertilizers

4.1.5.2.1 *Sulfur Fertilizers*. Sulfur fertilizers can be used either as nutrient fertilizers or for pH adjustment. This risk assessment considers these two uses of sulfur fertilizers as separate scenarios. According to the OPPT document, almost 60 percent of the potato acreage in the United States received sulfur and micronutrient fertilizers. This is a much greater percentage than any of the other field crops. The application rate for sulfur on potatoes also is much higher than other field crops (82 lb/acre for potatoes compared to 11 to 13 lb/acre for other field crops).

4.1.5.2.2 *Liming Materials*. A liming material is defined as “a product whose calcium and magnesium compounds are capable of neutralizing soil acidity” (AAPFCO, 1997b). Approximately 2,219,922 tons of lime fertilizer were used in the United States in 1996, corresponding to 3.6 percent of the total fertilizer consumption. Among individual states, North Carolina (947,126 tons) and California (621,915 tons) consumed the largest amount of liming materials. Liming materials may include recycled waste materials such as cement kiln dust (CKD).

4.1.5.2.3 *Gypsum Products*. Gypsum is defined as “a product consisting chiefly of calcium sulfate with combined water ($CaSO_4 \cdot 2H_2O$) . . . capable of neutralizing soil acidity. It occurs in large deposits of soft crystalline rock and as sand. A granulated form has been developed for application to soil (for growing peanuts and other crops) as a calcium source or a sulfur source either by itself or in a blend of other fertilizers. In irrigated agriculture, it is used to increase permeability of soils” (Fertilizer Dictionary, *Farm Chemicals Handbook*, 1997).

According to the OPPT document, about 50 percent of the secondary nutrient and micronutrient fertilizers (1,371,644 tons) were gypsum products.

4.1.5.3 Micronutrient Fertilizers. Zinc, manganese, boron, and iron fertilizers are the micronutrients considered in this report. Although micronutrients are essential for normal plant growth, they are required in relatively small amounts. According to the OPPT document, about 1.5 percent of the secondary nutrient and micronutrient fertilizers were zinc fertilizers (41,149 tons), while about 1 percent of the secondary nutrient and micronutrient fertilizers were iron fertilizers (27,432 tons). Studies have documented the presence of heavy metals in zinc micronutrient fertilizers (Mortvedt, 1985). Zinc micronutrient fertilizers are known to include recycled waste materials such as K061 and tire ash.

4.2 Geographic Location and Associated Parameters

Geographic location determines numerous significant factors in a risk analysis. Distributions of climate and soil parameters, key components of the risk assessment, are determined based on geographic location. This section describes the meteorological regions assessed in this analysis and identifies and provides information on key climate, soil, and crop data used to conduct the assessment.

4.2.1 Meteorological Regions

This analysis assesses the use of fertilizers in 29 meteorological regions within the continental United States. The 29 meteorological stations representing those regions are listed in Table 4-4. A map delineating the 29 meteorological regions is provided in Figure 4-1. The meteorological regions are identified in an assessment conducted for EPA's Superfund soil screening levels (SSLs) program (Environmental Quality Management, Inc. [EQM], 1993). These meteorological data are considered representative of both broad geographic climate regions that characterize the continental United States and more narrowly defined meteorological stations for which data are available throughout the United States. This section describes the methodology used to select these 29 regions.

In the Superfund analysis, meteorological data derived primarily from the Support Center for Regulatory Air Models (SCRAM) bulletin board, which provides information on 200 meteorological stations in the United States, were used to subdivide the continental United States into 29 meteorological regions. The SCRAM bulletin board can be accessed at http://www.epa.gov/scram001. The 29 meteorological stations are distributed among 9 general climate regions based on meteorological representativeness and variability across each region. These regions are the North Pacific Coastal, South Pacific Coastal, Southwest, Northwest Mountains, Central Plains, Southeast, Midwest, Northern Atlantic, and South Florida.

Once the regions were identified, large-scale regional average meteorological conditions were used to select representative meteorological stations within each of the 29 regions. Based on statistical analyses, the 29 meteorological stations were determined to be representative of the 200 meteorological stations in the United States for which data are available from the SCRAM bulletin board.

The 29 regions were then further refined using a geographic information system (GIS), which integrates climate and meteorological data from various geographic databases. The GIS data were used to construct more accurate meteorologic-based boundaries around each station. This effort was undertaken to ensure that each region represented an area in which the meteorological conditions were most similar to conditions measured at the meteorological station. As a first step in this process, the boundaries were adjusted to correspond to Bailey's ecological divisions and provinces (Bailey, 1996). Bailey's regions are defined primarily on physiography and climate. Bailey recognizes all natural ecosystems by differences in climatic regime. Climate, as a source of energy and moisture, acts as the primary control of the ecosystem. Other important criteria for establishing the limits of ecosystems are soil and landform. Thus, by using Bailey's ecoregions to help define the boundaries of the climate region landforms, soil and climate were considered.

Table 4-4. Meteorological Stations

	Meteorological Station		Latitude		Longitude	
City	**State**	**Number**	**Degree**	**Minute**	**Degree**	**Minute**
Albuquerque	NM	23050	35	3	106	37
Atlanta	GA	13874	33	39	84	25
Bismarck	ND	24011	46	46	100	45
Boise	ID	24131	43	34	116	13
Casper	WY	24089	42	55	106	28
Charleston	SC	13880	32	54	80	2
Chicago	IL	94846	41	59	87	54
Cleveland	OH	14820	41	25	81	52
Denver	CO	23062	39	46	104	52
Fresno	CA	93193	36	46	119	43
Harrisburg	PA	14751	40	13	76	51
Hartford	CT	14740	41	56	72	41
Houston	TX	12960	29	58	95	21
Huntington	WV	03860	38	22	82	33
Las Vegas	NV	23169	36	5	115	10
Lincoln	NE	14939	40	51	96	45
Little Rock	AR	13963	34	44	92	14
Los Angeles	CA	23174	33	56	118	24
Miami	FL	12839	25	49	80	17
Minneapolis	MN	14922	44	53	93	13
Philadelphia	PA	13739	39	53	75	15
Phoenix	AZ	23183	33	26	112	1
Portland	ME	14764	43	39	70	19
Raleigh-Durham	NC	13722	35	52	78	47
Salem	OR	24232	44	55	123	0
Salt Lake City	UT	24127	40	47	111	57
San Francisco	CA	23234	37	37	122	23
Seattle	WA	24233	47	27	122	18
Winnemucca	NV	24128	40	54	117	48

Source: EQM (1993).

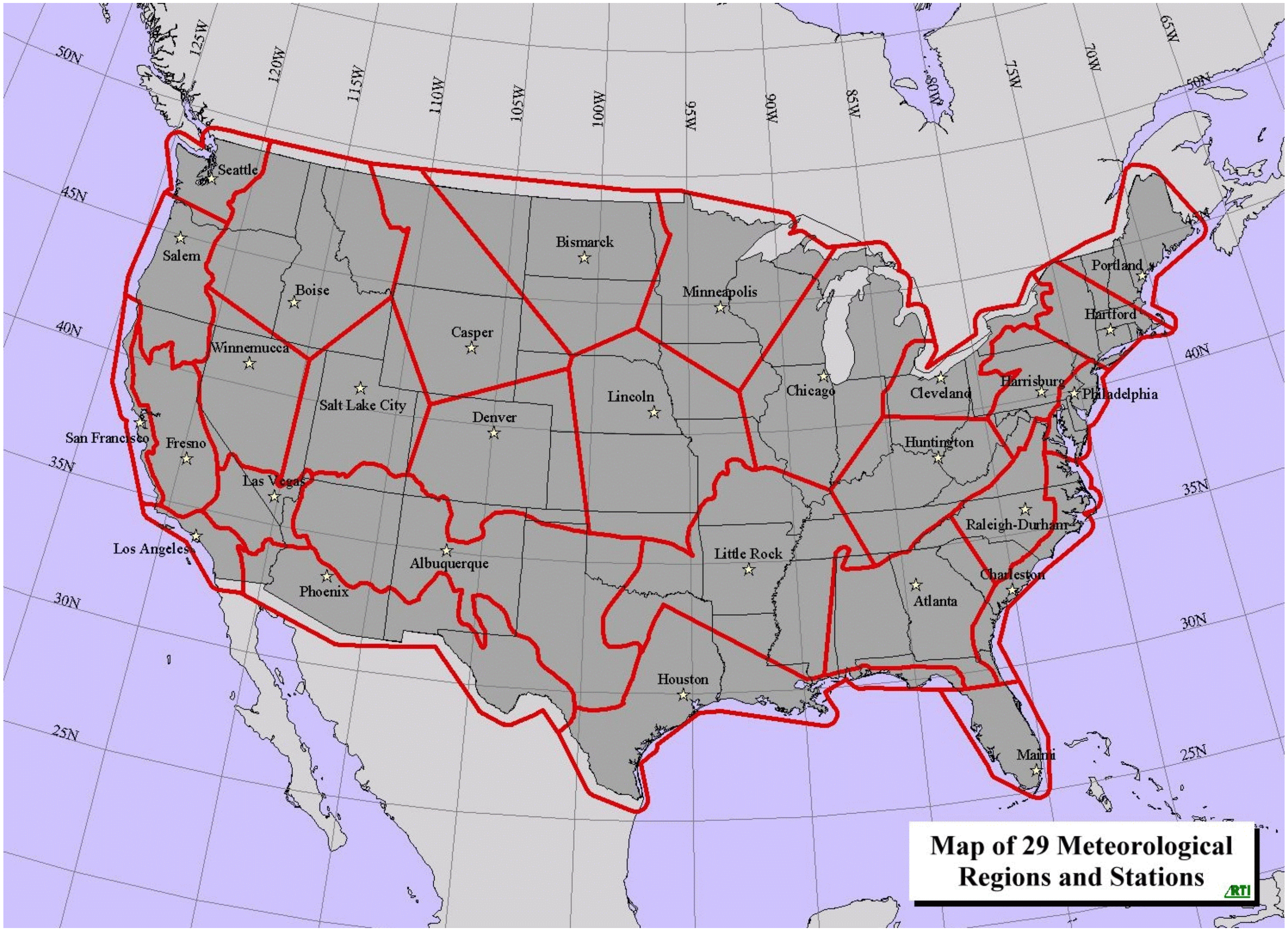

Figure 4-1. Map of 29 meteorological regions and stations.

Next, the Agency evaluated other physiographic features not addressed in Bailey's criteria but likely to influence climate conditions in certain atypical climatic areas. This evaluation helped ensure that the following unique regions were addressed within the selected regions: coastal regimes, which are dominated by coastal climate effects (these are generally narrow regions stretching about 25 to 50 miles inland); tropical/subtropical and arid/semiarid divisions in the southwestern United States; and northwestern regions within Washington, Oregon, and California, which are characterized by the more humid marine/redwood or Mediterranean mountain regimes. General wind regimes also were considered in defining the 29 regions. The data from the 29 selected meteorological stations were considered to be representative of the climate regions, and all modeling was conducted using these data.

4.2.2 Agricultural Land Use

This analysis is limited to fertilizer application to agricultural soil. The assessment used the Geographic Information Retrieval and Analysis System (GIRAS) (EPA Office of Information Resource Management [OIRM], 1994) to identify geographic areas used for agriculture. GIRAS provides comprehensive land use data in digital GIS format. The GIRAS database designates agricultural land as Anderson Level I: Land Use Code 2. At the next level (Level II), agricultural lands are divided into subcategories of agricultural use. These categories are designated as Anderson Level II: Land Use Codes 21 through 24 (see Table 4-5).

4.2.3 Climate Data

Detailed climate and meteorological data are required to model primary exposure pathways. Meteorological data (e.g., rainfall) are needed to model erosion and overland transport of soil from fertilizer-amended fields to adjacent fields and waterbodies and to model air dispersion and deposition to estimate concentrations of constituents in surrounding areas due to windblown dust and particles from agricultural fields.

The National Climate Data Center (NCDC) is maintained by the National Oceanic and Atmospheric Administration (NOAA) in partnership with regional and state climatologists. These data are used to obtain annual precipitation, average annual temperature, and annual average wind speed for use in modeling. NCDC climate data for the 29 meteorological regions are integrated into EPA's GIS platform, described earlier.

Table 4-5. Anderson Land Use Codes Used to Identify Agricultural Land Use in the GIRAS Database

Level I	Level II	
Code 2 Agricultural Land	Code 21	Cropland and Pasture
	Code 22	Orchards, Groves, Vineyards, Nurseries, and Ornamental Horticultural Areas
	Code 23	Confined Feeding Operations
	Code 24	Other Agricultural Land

A variety of meteorological input is needed to conduct air dispersion modeling. This analysis uses 5 years of representative surface and upper air data for each of the 29 meteorological regions modeled to determine long-term average air dispersion and deposition estimates.

Surface data were obtained from the Solar and Meteorological Surface Observation Network (SAMSON) CD-ROM (NOAA, 1993) for each meteorological station. These data include 5 years of hourly observations of the following surface meteorological parameters:

opaque sky,
temperature,
wind direction,
wind speed,
ceiling height,
current weather,
station pressure, and
precipitation type and amount.

The corresponding upper air data were obtained from EPA's SCRAM bulletin board. These data were paired with the surface data for air dispersion modeling using the meteorological preprocessor PCRAMMET. PCRAMMET pairs the surface data with the upper air data to create a meteorological file that contains hourly wind speed, wind direction, atmospheric stability class, temperature, and mixing height. PCRAMMET requires additional inputs based on site-specific land use data. These inputs were developed for each meteorological location based on GIRAS data.

Climate data were linked through a GIS platform to other geographically dependent data, such as agricultural land use, soil property parameters, and crop type, for estimating a nationwide distribution of risk from the application of fertilizer products.

4.2.4 Soil Data

The physical and chemical properties of soil are among the most important parameters affecting the fate and transport of metals and dioxins in agricultural environments. They also are among the most difficult to simulate realistically through the use of fate and transport models.

Soil characteristics are critical determinants of metal speciation and mobility in the environment. Important soil-related parameters used in this risk assessment to model the movement of metals and dioxins in the environment are provided in Table 4-7. A brief description of some of the most important soil and soil-related parameters that affect metal speciation and mobility is provided here. Data sources also are described in the following section.

Note that not all of the soil-related parameters discussed here were used in this risk assessment. Relationships between many critical soil parameters (e.g., pH, clay content) are very complex and cannot be estimated by the simple systems used for fate and transport modeling in this risk assessment. Instead, complex interactions among soil parameters are addressed only indirectly in this risk assessment through the use of empirically derived soil-water distribution coefficients (K_ds) and soil-plant uptake factors (Brs) for metals.

Soil-water distribution coefficients and Brs may be used to account for varying interactions among critical soil parameters, such as pH and clay content, because these parameters ultimately affect the K_ds and Brs for metals. Therefore, to the extent possible, this analysis accounts for the interaction among multiple soil parameters by using a distribution of measured values collected from the literature for K_ds and Brs. Distributions of these values were selected that reflect actual agricultural soil conditions in multiple locations across the country. This approach empirically addresses the variation in soil parameters, such as pH and clay content, that cannot be addressed by modeling.

Although the K_ds and Brs were used to account for varying interactions among critical soil parameters, note that the K_d and Br values are metal-specific and do not account for competition among multiple metals. Specifically, model simulations were performed for systems comprised of one single metal at a time (i.e., the potential for competition between multiple metals for available sorbent surfaces was not considered). Generally, competition of multiple metals for available sorption sites results in higher dissolved metal concentrations than would exist in the absence of competition; however, this effect is most significant at greater concentrations than those of the systems evaluated for this analysis, with the possible exception of zinc and cadmium interactions. Studies show that when the cadmium-to-zinc ratio is relatively high, the plant uptake of cadmium from the soil is greatly increased because less zinc is available to inhibit the uptake (personal communication from Rufus Chaney, 1999). When this ratio is relatively low, zinc is phytotoxic before significant quantities of cadmium can accumulate in plant tissues. Although phosphate fertilizers are characterized by relatively high cadmium-to-zinc ratios and may have enhanced cadmium bioavailability, this relationship and other interactions among metals were not considered in the model simulations conducted for this risk assessment.

4.2.4.1 Critical Soil Parameters. This section identifies critical soil parameters and describes how they affect metal speciation and migration in soil. Because climate factors can influence the behavior of metals in soil, important climate factors also are identified.

As noted earlier, not all the parameters discussed in this section were used in the quantitative fate and transport modeling conducted for this risk assessment. Therefore, the following discussion also provides information on which parameters were used directly in the fate and transport modeling and how they were applied.

Soil Texture/Type—Soil texture affects the migration of metals through the soil column. For example, water infiltrates more readily through permeable sandy soil that is low in clay and organic matter than through soil characterized by a high clay and/or organic matter content. Consequently, leaching or migration of metals is favored in sandy soil. Hydrologic soil groups are used to describe soils with similar runoff and leaching characteristics. The chief consideration in designating hydrologic soil groups is the inherent capacity of the soil to permit infiltration. The predominant soil texture characterizing selected map unit identifiers (MUIDs) in the continental United States (CONUS) database was determined and then used to obtain values for soil parameters, including total porosity, residual water content, soil dry bulk density, and saturated hydraulic conductivity, all of which are specific to the soil texture identified. These data were obtained from Carsel and Parish (1988) and used as inputs to the soil partitioning and fate and transport model described in Section 5.

Fraction Organic Carbon (f_{oc})—Organic matter content is an important parameter in assessing the fate and mobility of metals in the environment because it represents surfaces to which metals may sorb. Metals tend to bind to the net negatively charged organic matter. If sufficient binding sites are available and if the thermodynamics of the system favor metal sorption, less metal will be available for transport in the dissolved state. In contrast, if there are insufficient sites available for metal sorption to take place, the metal will remain in the dissolved, more bioavailable state. The f_{oc} was calculated based on the organic matter content of the soil, which is available by MUID in the U.S. Soils (USSOILS) database. The f_{oc} was used directly in the soil partition model described in Section 5.

Soil pH—The pH of the soil system describes the acid-base properties of the background pore water. The pH is an important parameter in assessing the fate and mobility of metals in the environment because it has a direct effect on metals speciation. Metals are generally most soluble under acidic conditions (pH <6), although some are also highly soluble under highly alkaline conditions.

Soil pH was not used directly as a modeling parameter in this analysis. Instead, the soil pH was addressed as a function of how it affected the K_d and Br values. For this analysis, empirically derived values available from the literature were used to define the distribution of K_ds and Brs characteristic of agricultural soils. Variations in pH that occur within the range appropriate for agricultural soils were assumed to be addressed through the use of representative distributions of measured K_d and Br values provided in the literature.

Soil-Water Distribution Coefficients (K_ds)—K_ds describe metal partitioning between environmental substrate and aqueous phases. Metal partitioning is important in assessing the fate and mobility of metals in the environment. Metals that favor partitioning to the substrate are less likely to be available in the dissolved phase.

The K_d is metal-specific as well as system-specific. Depending on the metal and the system parameters, the K_d can range over as many as six or seven orders of magnitude. Ranges of this size present a challenge in the estimation of a single generic K_d value for use in risk assessment models. This analysis used K_d distributions that were compiled from K_d values reported in the scientific literature. Distributions of empirically derived K_ds were used directly as inputs to the soil partitioning model described in Section 5. The database of K_d values compiled by EPA for use in this effort is provided in Appendix D. Appendix B provides a discussion of the use of models to derive K_d values and the limitations of using modeled K_ds.

Distribution coefficients also were used to model the risk associated with the dioxin congeners. In this case, the K_d was calculated as follows:

$$K_d = K_{oc} \text{ x } f_{oc} \tag{4-1}$$

where

K_d = distribution coefficient (kg/L or g/cc)
K_{oc} = organic carbon-water partition coefficient (L/kg)
f_{oc} = fraction organic carbon (unitless).

Climate Trends—Precipitation and temperature are the most important attributes of climatic conditions that influence the behavior of metals in soil. Increased precipitation increases the volume of leachate and runoff. In addition, an increase in precipitation most likely will increase the biomass of vegetation with varying effects on soil, depending on temperature. The following parameters were varied by climate region and used directly in the soil fate and transport models described in Section 5:

- average annual precipitation,
- average annual evapotranspiration,
- average annual runoff,
- temperature, and
- mean annual wind speed.

4.2.4.2 <u>Sources of Soil Data</u>. This section provides an overview of readily available sources that contain data on the physical and chemical properties of soils in the United States based on geographic location. Specific data sources for each of the soil-related parameters used in this risk assessment are provided in Table 4-7.

State Soil Geographic (STATSGO) Database—This database is maintained by the Natural Resources Conservation Service (NRCS). The STATSGO database was designed primarily for regional, multicounty, river basin, state, and multistate resource planning, management, and monitoring. These data are collected as part of the National Cooperative Soil Survey (NCSS). STATSGO combines soil data from individual states to provide integrated nationwide coverage of the conterminous United States, Alaska, Hawaii, and Puerto Rico. Soil maps for STATSGO are made by generalizing the detailed soil survey data. The scale for STATSGO maps is 1:250,000. The STATSGO database is described in greater detail in Appendix C.

USSOILS Database—This is a smaller database that contains selected variables from the STATSGO data set. USSOILS contains selected erosion and hydrologic variables from the STATSGO data set, including

- available water capacity of the soil,
- percentage of clay in the soil,
- soil erodibility (k-factor) used in the water erosion component of the universal soil loss equation (USLE),
- organic matter content in the soil,

- soil permeability,
- cumulative thickness of all soil layers,
- hydrologic characteristics of the soil,

quality of drainage,
surface slope,
liquid limit of the soil,
fraction of a map unit with hydric soils, and
annual frequency of flooding.

The USSOILS database was originally compiled to support a national model of water quality. USSOILS aggregates the STATSGO layer and component information within a map unit by depth-averaging median properties over the entire soil column within a unit component and then area-averaging component values across a map unit. The soil property data obtained from the USSOILS database for this analysis were the organic matter content and the soil erodibility factors. Metadata on STATSGO and USSOILS may be found online at http://www.ftw.nrcs.usda.gov/stat_data.html.

Continental United States (CONUS) Database—This database also contains selected variables from the STATSGO data set, including

soil texture class,
depth to bedrock,
fraction of sand,
fraction of silt,
fraction of clay,
rock fragment class,
rock volume class,
bulk density,
porosity,
hydrologic soil groups, and
available water capacity.

The CONUS soil data set was compiled by the Earth System Science Center in the College of Earth and Mineral Sciences at Pennsylvania State University for application to a wide range of climate, hydrology, and other environmental models (Miller and White, 1998). CONUS contains STATSGO soil properties averaged to a depth of 2.5 m for 11 standard layers. The depths of the layers are given in Table 4-6. This analysis is concerned only with the top three

Table 4-6. Soil Layer Thickness

Layer	Thickness (cm)
1	5
2	5
3	10
4	10
5	10
6	20
7	20
8	20
9	50
10	50
11	50

layers of soil (top 20 cm). Within each STATSGO map unit and CONUS standard layer, soil properties represent either the predominant property (as with soil texture) or area-weighted averages of STATSGO component values. Data obtained from the CONUS database were the predominant soil textures and the percentage of silt. Additional information on CONUS can be found at http://www.essc.psu.edu/soil_info/index.cgi?soil_data&conus.

Carsel and Parrish (1988)—The data obtained from the databases described earlier were also linked to soil descriptions of standard soil types provided in Carsel and Parrish (1988). This linked reference was used to derive the following soil-related parameters:

- total porosity (unitless),
- saturated hydraulic conductivity (cm/h),
- saturated volumetric water content (mL/cm^3), and
- residual water content (unitless).

Soil Dry Bulk Density—The dry bulk density of soil was calculated using parameters derived from Carsel and Parish (1988) in accordance with the following equation:

$$B_d = \rho\,(1-n) \qquad (4\text{-}2)$$

where

B_d = dry bulk density (kg/L or g/cm^3)
ρ = particle bulk density (assume 2.65 g/cm^3, quartz)

n = total porosity = saturated water content.

The dry bulk density equals 1.51 g/cm^3 for a loam with a saturated water content equal to 0.43.

EPA Database of Distribution Coefficients (K_ds)—K_ds used for this analysis were taken from a recently compiled EPA database of empirically derived K_d values reported in the scientific literature (Appendix D). In the EPA-generated database used for this analysis, the K_ds are compiled on a metal-by-metal basis for a range of environmental systems. EPA's compilation of K_d values was developed for multiple projects, each characterized by its own set of specific criteria. More than 200 papers were reviewed and the pertinent data recorded in spreadsheets. The geochemical parameters (e.g., pH, soil type, total metal concentration, dissolved organic carbon content, particulate organic carbon content, iron oxide content) most likely to influence the K_d were also entered into the spreadsheets, if provided in the paper.

For this fertilizer analysis, EPA used only K_d values derived for settings that most closely approximate the conditions found in agricultural soil. Soil pH and soil type were used to cull the data set for the fertilizer risk assessment. Other geochemical parameters were also considered for this purpose (e.g., total metal concentration, organic matter content, iron oxide content). This type of information, however, was less consistently reported in the literature.

A more detailed discussion of the significance of K_ds for this assessment, the development of EPA's K_d database, and the selection of K_d values for this assessment is provided in Appendix D. The appropriate way to derive and use K_ds for fate and transport modeling of metals in soil was raised by peer reviewers of the CKD risk assessment. Peer reviewers' comments are provided in Appendix A and EPA's analysis of the issue is provided in Appendix B.

Table 4-7 provides a summary of the soil data used for this analysis and the sources from which the data were obtained.

4.2.5 Farm Size

A nationwide distribution of agricultural farm sizes was examined to select a single 90th percentile field size to be modeled in this analysis. The 1992 Agricultural Census was used as a source for the nationwide distribution of farm sizes, which presents data for the number of farms in each size range. Table 4-8 presents the data used in this analysis.

A cumulative distribution of farm sizes was developed based on the total number of farms and the number of farms within each size range. The size range that most closely approximates the 90th percentile was used in this analysis. Because air modeling is the most time-consuming step in this risk analysis, a single 90th percentile agricultural area was modeled. A sensitivity analysis was conducted to assess the effect that the selection of field size has on air dispersion and deposition modeling. This analysis is discussed briefly in Section 5 and in greater detail in Appendix E. EPA believes that this method provides a field size suitable for this nationwide analysis.

Table 4-7. Soil and Climate Data Used in Fertilizer Analysis

Soil Texture Type	Unit	Data Source
Dry bulk density of soil at application location	g/cm^3	Calculated from data in Carsel and Parrish (1998) based on dominant soil texture reported in CONUS soil database
Saturated volumetric water content of soil	mL/cm^3	Obtained from data in Carsel and Parrish (1998) based on dominant soil texture reported in CONUS soil database
Residual water content	unitless	Obtained from data in Carsel and Parrish (1998) based on dominant soil texture reported in CONUS soil database
Weighted average percentage of silt for top 20 cm	%	CONUS soil database
Fraction of organic carbon in soil at application location	unitless	Calculated using organic matter content reported in USSOILS database
Distribution coefficients (K_ds) for metals	L/kg	EPA database (See Appendix D)
Distribution coefficient (K_ds) for dioxin congeners	L/kg	Calculated in accordance with $K_d = K_{oc} \times f_{oc}$. The K_{oc} is congener specific. See Appendix K for additional details.
Average annual precipitation	cm/yr	NOAA, 1992
Average annual evapotranspiration	cm/yr	Leeden, 1990
Average annual runoff	cm/yr	Leeden, 1990
Temperature	K	NOAA, 1992
Mean annual wind speed	m/s	NOAA, 1992
USLE rainfall/erosivity factor	yr^{-1}	USDA, 1978
USLE soil erodibility factor	tons/acre	USSOILS database

Table 4-8. Data Used in Selection of Farm Size for Fertilizer Risk Assessment Modeling

Farm Size Range	Average Farm Size (acres)	Average Farm Size (m^2)	Number of Farms in Size Range	Cumulative Percentile of Farms in Size Range
1 to 9 acres	5	20,235	326,020	0.0849253
10 to 49 acres	29.5	119,387	722,552	0.2861681
50 to 69 acres	59.5	240,797	239,228	0.3484849
70 to 99 acres	84.5	341,972	326,958	0.4336545
100 to 139 acres	119.5	483,617	323,178	0.5178395
140 to 179 acres	159.5	645,497	277,982	0.5902513
180 to 219 acres	199.5	807,377	188,958	0.6394731
220 to 259 acres	239.5	969,257	155,232	0.6799097
260 to 499 acres	379.5	1,535,837	510,670	0.8129346
500 to 999 acres	749.5	3,033,227	372,624	0.91
1,000 to 1,999 acres	1,499.5	6,068,477	203,746	0.963074
2,000 acres or more	>2,000	>8,094,000	141,756	1

The total areas of the farms within a given size range were summed and the total area divided by the number of farms in the size range to determine the average size of a farm within that size range. This area was used in the fertilizer risk assessment modeling.

Because all fertilizer products were assumed to be applied based on the mass per unit area, the size has no effect on the soil concentration due to fertilizer application. Field size does, however, correlate positively with the quantity of vapors and particulates that are assumed to become airborne and dispersed and redeposited on plants and soil and in nearby waterbodies. The field size also is positively correlated with the quantity of soil eroded from the field and deposited in the nearby stream.

4.2.6 Crop Types and Plant Uptake Factors

4.2.6.1 Crop Types. The 1992 Agricultural Census database indicates which crops are produced commercially in each county in the United States. These data are compiled and maintained by the Government Information Sharing Project at Oregon State University, Information Services Census of Agriculture: 1982, 1987, 1992 (available online at http://govinfo.kerr.orst.edu/ag-stateis.html). For this analysis, the list of specific crops presented in the Agricultural Census was evaluated and grouped into five categories: grains, forage, fruit, herbage, and roots. These categories correspond to categories for which plant uptake factor data are available. Plant uptake factors are discussed in the following section. The total number of acres of each crop in each category was selected from the database by county. Data for the counties within each of the 29 climate regions were summed. The total area within each climate region where each crop is reported harvested was summed. Detailed data used in this analysis are presented in Appendix F.

4.2.6.2 Plant Uptake Factors. Plant uptake factors estimate the concentration of contaminants in plant tissue as a function of the concentration of contaminants in soil. EPA collected and compiled plant uptake data specifically for this assessment. References on plant uptake were identified from the following sources:

- California Department of Food and Agriculture (CDFA) report on risk-based concentrations for certain metals in fertilizers (CDFA, 1998);

- Oak Ridge National Laboratory report, *Methods and Tools for Estimation of the Exposure of Terrestrial Wildlife to Contaminants* (Sample et al., 1997); and

- Chaney and Ryan's *Risk Based Standards for Arsenic, Lead, and Cadmium in Urban Soils* (Chaney and Ryan, 1994).

References cited in these sources were collected, and relevant and appropriate data were compiled in a plant uptake factor database. In addition, data were entered into the database directly from the following source without obtaining original citations:

- Oak Ridge National Laboratory report, *Empirical Models for the Uptake of Inorganic Chemicals From Soil By Plants* (Bechtel Jacobs, 1998).

The entire database was then assessed based on the discussion in Chaney and Ryan (1994) regarding the development of uptake factors. The sources used to populate the plant uptake database include data from both field studies and greenhouse studies. According to Chaney and Ryan (1994), greenhouse studies have been reported to result in higher metal uptake than field studies and, therefore, are considered less representative of agricultural settings. Using only field data is generally recommended for developing plant uptake factors (Chaney and Ryan, 1994). Consequently, for this analysis, EPA excluded data from greenhouse studies and relied solely on field data for all metals, with the exception of nickel and zinc for which insufficient field data were available. EPA supplemented the field data for these two metals with data from greenhouse and pot studies. Greenhouse data were used for zinc uptake factors for fruits, grains, and roots and for nickel uptake factors for fruit. The plant uptake database as well as a more detailed discussion of the data sources and the database development are provided in Appendix G.

Most of the sources of plant uptake data include information on the part of the plant for which constituent concentrations were measured. Although the terminology used and the level of specificity varies among reports (e.g, above-ground parts, herbage, stems), the plant parts addressed can be divided into a few general categories. The following plant part categories were used to categorize uptake factor data in this risk assessment:

- roots,
- herbage (nonreproductive aerial parts),
- fruits (reproductive parts, including fruits, flowers, nuts, and seeds),
- grains, and
- forage (nonreproductive aerial parts consumed by animals but not by humans).

Metal contaminants are differentially translocated throughout the roots and aerial parts of plants. These categories are based on discussions in the data sources and in general texts on plant uptake mechanisms and translocation (Farago, 1994; Fitter and Hay, 1983; Raven et al., 1982; Wilkins, 1990). The derivation of plant categories is further described in Appendix G.

4.2.7 Integration of Geographic Data

The geographic databases described in this section were accessed through the GIS platform used for this assessment. Use of the GIS platform allowed for determination of all of the required soil parameters at geographic locations in the United States. Because soil information was reported by county, soil data were aggregated by meteorological region and data distributions were developed for each region. These soil data were linked through the GIS platform to other geographically dependent data, such as climate parameters, agricultural land use, and crop type, to estimate a nationwide distribution of risk from the application of fertilizer products.

4.3 Description of Receptors and Pathways

4.3.1 Receptors

The receptors in this risk analysis are farmers and their children who are exposed on a farm where the fertilizer product is applied as directed. Farm children aged 1 to 5 years are evaluated for this analysis. The relevant exposure routes are

- Direct ingestion of fertilizer product during fertilizer application,

- Ingestion of soil amended with fertilizers,

- Inhalation of particles and vapors in the air during and after fertilizer spreading and tilling, and

- Ingestion of plant and animal products produced on soil amended with these products.

Farmers are assumed to raise a substantial portion of the food consumed on their own farms, including fruit, above-ground vegetables, root vegetables, and beef and dairy products.

Because the fertilizer product is applied directly to the agricultural field, all exposures to plant and animal products are assumed to occur where the products are used. Inhalation exposure by the farmer and child was also estimated on the farm. This is not an unrealistic assumption because in farming communities residences may be surrounded by agricultural fields amended with similar fertilizer materials. In this risk assessment, the farmer also is a fisher who consumes a portion of fish caught from a stream adjacent to a large field amended with a fertilizer product. A summary of risk assessment pathways and receptors considered in this analysis is provided in Table 4-9.

The risks for all ingestion pathways for a single constituent are assumed to be additive. Ingestion exposures are assumed to occur in the same time frame for the same individuals, and the same health benchmark is applicable to all ingestion exposures. For constituents with noncancerous endpoints, inhalation exposure is additive to ingestion exposure only if the same human health benchmark endpoint is applicable to both pathways. Similar additions of risk may be made for different metals in the same product. For metals, however, only arsenic is considered a carcinogen by the oral route. All other metals are not carcinogenic by the oral route and do not have common health benchmark endpoints; thus, ingestion exposures to different metal constituents in a single product are not considered additive. No other metal exposures are considered additive because there are no common target organs for the noncancerous human health benchmarks for these metals.

Table 4-9. Summary of Risk Assessment Pathways and Receptors

Pathways	Adult Farmer	Child of Farmer
Inhalation Pathways		
Windblown emissions	✓	✓
Application and tilling	✓	✓
Ingestion Pathways		
Ingestion of product	✓	
Ingestion of soil	✓	✓
Ingestion of vegetables	✓	✓
Ingestion of fruits	✓	✓
Ingestion of root vegetables	✓	✓
Ingestion of beef and dairy products	✓	✓
Ingestion of home-caught fish	✓	✓

Each fertilizer product is assumed to be applied independently of all other products. No addition of risk is assumed among products. There are no data to document co-application of multiple products, so none were considered in this risk assessment.

4.3.2 Exposure Pathways

All exposure pathways evaluated are assumed to occur as a result of recommended use procedures for fertilizer products. Each of the pathways presented here has been evaluated in this risk analysis:

Product→human ingestion

Product→soil→human ingestion

Product→soil→air→human inhalation

Product→soil→air→plant→human ingestion (above-ground vegetable, fruit)

Product→soil→air→plant→cattle→human ingestion (beef and dairy through forage and silage)

Product→soil→plant→human ingestion (above-ground vegetable, fruit, root vegetable)

Product→soil→plant→cattle→human ingestion (beef and dairy through grain, forage and silage)

Product→soil erosion→stream→fish→human ingestion

Product→soil→air→stream→fish→human ingestion

Each exposure pathway is described in the following section. Information on the exposure factors necessary for this risk analysis (i.e., food intake rates, exposure duration) and the assumptions used in the risk estimations are provided in Section 6.

4.3.2.1 **Product→Human Ingestion**. During handling of the product ingestion, the farmer may inadvertently ingest some of the product through hand-to-mouth actions. This ingestion is assumed to occur only during fertilizer application periods. The state of California estimated that this operation would occur on 16 days per year for primary fertilizer application, and the same assumption has been made in this risk assessment. Generally, micronutrient fertilizers are applied less frequently than macronutrient fertilizers (The Fertilizer Institute [TFI], 1999). Micronutrient fertilizer application is assumed to occur at half the rate of macronutrient fertilizer application, or 8 days per year. This assumption is consistent with assumptions made by TFI in a recently published assessment of fertilizer applicators (TFI, 1999). Incidental ingestion of fertilizer is evaluated only for the farmer or farm worker who is assumed to be the fertilizer applicator for this risk analysis.

4.3.2.2 Product→Soil→Human Ingestion. Children and adults are assumed to ingest soil to which a fertilizer has been applied. Soil and dust ingested by children and adults is assumed to have concentrations of metals and dioxins resulting from 100 years of fertilizer application. Children are assumed to ingest much higher quantities of soil from ages one to six. After age 7, children's soil ingestion rates are assumed to be equivalent to those of adults. Children aged 1 to 5 were evaluated for this assessment.

4.3.2.3 Product→Soil→Air→Human Inhalation. Fertilizer-amended soil particles and vapors from amended fields are assumed to become airborne through continuous wind erosion and during tilling. Tilling is assumed to occur only during fertilizer application. In this risk assessment, fertilizer application is assumed to occur on 16 days each year for primary nutrient application and 8 days each year for micronutrient application. Farmers and their children are assumed to inhale the annual average concentration of particles and vapors averaged over the area of the agricultural field.

4.3.2.4 Product→Soil→Air→Plant and Soil→Plant→Human Ingestion (Above-Ground Vegetable, Fruit, Root Vegetables). The vapors and particles released due to wind erosion and tilling are assumed to deposit on the above-ground portions of the plants growing in the agricultural fields. Some of this material is assumed to be taken into the vegetation. The vegetation grown in the fertilizer-amended soil also absorbs the metals and dioxins directly through the roots. Farmers' and farm children's intake of fruits and vegetables are assumed to come from fields amended with the fertilizer product.

4.3.2.5 Product→Soil→Air→Plant→Cattle→Human Ingestion (Beef and Dairy). The metals and dioxin constituents in fertilizers are assumed to be taken into the plants used as forage, grain, and silage materials through their roots. In addition, constituents in soil are assumed to become airborne, and particles and vapors are assumed to deposit on the exposed portion of the plants and become incorporated into the plant tissue. Cattle are assumed to eat forage and to be fed grain and silage grown on fertilizer-amended soil. Cattle are also assumed to consume a quantity of soil while grazing in the field. A portion of the contaminated vegetation and soil is assumed to be incorporated into the lipid portion of the animal tissue based on constituent-specific food chain biotransfer factors. Farmers and their children then are assumed to ingest beef and dairy products from animals that have eaten contaminated produce and ingested contaminated soil. Constituent-specific food chain biotransfer factors are provided in Appendix K. Information on exposure assumptions (i.e., food intake rates, exposure duration) is provided in Section 6.

4.3.2.6 Product→Soil Erosion→Stream and Soil→Air→ Stream→Fish→Human Ingestion. Vapors and particles from wind erosion and tilling of agricultural fields are assumed to deposit in the stream adjacent to the agricultural field. In addition, soil is assumed to erode from the field to the stream. Contaminants reaching the stream are partitioned among the dissolved water column, the suspended solids, and the sediment based on distribution coefficients (Kd_{sw} = suspended sediment-surface water partition coefficient [L/kg] and Kd_{bs} = bottom sediment-sediment pore water partition coefficient [L/kg]). See Appendices D and K. The fish in the stream are assumed to be exposed to all constituents reaching the stream. Fish are assumed to incorporate a portion of the constituents into the lipid fraction of fish tissue based on constituent-specific biotransfer factors. Farmers and their children are assumed to ingest a portion of home-caught fish from this stream as a portion of their regular diet. Constituent-specific fish bioconcentration factors are provided in Appendix K. Dietary assumptions are provided in Section 6.

5.0 Estimating Exposure Point Concentrations

5.1 Exposure Pathways for Human Receptors

The human health risk assessment scenarios considered in this analysis are exposures to farmers and their children from metals and dioxins in fertilizer products applied at recommended rates and frequencies. Exposure is assumed to occur through both direct and indirect pathways; however, groundwater pathways are not considered. The direct pathways considered are the inhalation pathway, including the inhalation of particles and vapors from windblown emissions and from emissions during product application and tilling, and the ingestion pathways, including the direct ingestion of products during application and the ingestion of soil amended with the products. The indirect exposure pathways considered are ingestion of plants (vegetables, fruits, root vegetables, and grains) grown on soils amended with fertilizer products containing metals and dioxins, ingestion of beef and dairy products produced on land amended with these products, and ingestion of home-caught fish from a stream adjacent to the agricultural field.

The risks for all ingestion pathways for a single constituent are assumed to be additive. Ingestion exposures are assumed to occur in the same time frame in the same individuals, and the same health benchmark is applicable to all ingestion exposures. For constituents with noncancer endpoints, exposure through inhalation is additive to exposure through ingestion only if the same human health benchmark endpoint is applicable to both pathways. Similarly, additions of risk may be made across metals in the same product if the health benchmark endpoints are the same. All cancer endpoints are considered identical. For metals, however, only arsenic is considered a carcinogen by the oral and inhalation routes. All other metals are not carcinogenic by the oral route and do not have common health benchmark endpoints; thus, ingestion exposures to different metal constituents in a single product are not considered additive. Inhalation risks for arsenic, chromium VI, and nickel refinery dust may be considered additive because all have cancer as the human health benchmark endpoint. No other metal exposures are considered additive because there are no common target organs for the noncancer human health benchmarks for these metals.

5.2 Determining Exposure Point Concentrations for Human Receptors

5.2.1 Probabilistic Methodology for Determining Exposure Point Concentrations

This risk assessment uses a probabilistic (i.e., Monte Carlo) methodology to estimate a distribution of lifetime risk to the farmer and farm child from 9 metals and 17 dioxin congeners in each of the 13 fertilizer products applied to crops in the 29 climate regions. Risks are estimated based on distributions of exposure point concentrations of the hazardous constituents estimated in fertilizer, fertilized soils, surface water, plant tissue, and animal tissue. These media concentrations are combined with distributions of assumptions regarding exposures to fertilizers, amended soils, and/or contaminated food products.

A Monte Carlo simulation is used to approximate the effects of natural variability that often accompany many actual environmental conditions. In addition, information on the distribution (range and likelihood) of possible values for these parameters is produced using this technique. When compared with alternative approaches for assessing parameter variability, the Monte Carlo technique has the advantages of being generally applicable, with no inherent restrictions on input distributions or input-output relationships, and of using relatively straightforward computations. Also, Monte Carlo results can be used satisfactorily to describe uncertainty and to quantify the degree of conservativeness used. Potential limitations exist, however, when applying Monte Carlo techniques in modeling efforts. For example, variability (inherent variation in a measure over time and space) and uncertainty (lack of knowledge) are often difficult to distinguish within applications. Also, sufficient data must be gathered to ensure that representative distributions are statistically valid. A more detailed discussion of uncertainties, variability, and data limitations of parameters varied in this Monte Carlo analysis is provided in Section 8. A description of the Monte Carlo methodology used in this risk assessment is described below.

Monte Carlo simulation is a statistical technique that calculates an individual risk value repeatedly using randomly selected inputs for each parameter in the risk assessment scenario for each calculation. The Monte Carlo methodology used in this analysis provides an assessment of risk across 29 climate regions to farmers and farm children for each of the fertilizer products evaluated. The following discussion describes the probabilistic methodology used to process and integrate the large numbers of variables (e.g., product categories, climate regions, soil parameters) required to estimate distributions of exposure point concentrations resulting from use of fertilizers and other soil amendments.

First, the distribution of variables within the product and constituent category of parameters that affect or determine risk is defined and entered into the Monte Carlo simulation model. Crystal Ball software generates a large number of randomly generated input variables used in fate and transport modeling. Input variable distributions are generated independently for each category of variable. For example, for each of the 13 fertilizer product categories, distributions of concentrations of each metal constituent and of application rates for the product are defined in Crystal Ball. This software is then used to randomly sample the distributions of concentrations and application rates for a minimum of 1,000 times to generate 1,000 combinations of concentrations and application rates. These 1,000 combinations are then used as input variables for each type of fertilizer. This generates 13 sets of product-specific input files. The same methodology is used to develop distributions of soil-water distribution coefficients and soil-plant uptake values specific to each of the nine metal constituent files.

The approach for the climate file is slightly different. In order to maintain the relationship among the geographically based variables, all parameters from geographic information system (GIS) databases are linked according to map unit identification (MUID). All climate file data variation is based on the selection of a random MUID. This process maintains the relationship known to exist among the soil parameters because all geographically linked data remain linked throughout the analysis. For example, the percentage of silt used in the particulate air emission equations is matched with the appropriate soil fraction organic carbon (foc) and precipitation data for that same location.

The total number of input files required for the analysis was, therefore, limited to 13 product files, 9 constituent files, 29 climate region files, and 1 exposure parameter file. The analysis was coordinated by a computer program that selects a row of inputs from each of the appropriate files and copies them to the appropriate locations in the existing fate and transport model, calculates the exposure point concentrations and risks, and extracts the required results. The results for each iteration of the model for each constituent are then saved in a file specific to each combination of product and climate region. This process produces 1,000 results for each exposure point concentration and risk by pathway for each metal in each product and climate region combination. From these results, the percentile distribution of exposure point concentrations and risks can be determined for each product in each climate region.

Parameters varied in this analysis are presented below. Distributions of data were developed only for application rates and all exposure parameters. Other parameters were varied among measured data points.

- Fertilizer Composition – Fertilizer-specific concentrations of metals and dioxins.

- Fertilizer Application – Fertilizer-specific application rates and frequencies.

- Geographic Location – Meteorologic parameters (varied by climate region):
  - Precipitation
  - Irrigation
  - Evapotranspiration
  - Runoff from the agricultural field
  - Wind speed
  - Temperature
  - Soil erosivity
  - Soil erodibility

  Soil parameters (varied by map unit):
  - Bulk density
  - Total porosity
  - Residual water content
  - Percent silt
  - Fraction organic carbon.

- Hazardous Constituent-Specific Parameters – Soil-water partition coefficients (K_ds) and plant biouptake factors (Brs).

- Exposure Factors – Soil intake, fruit and vegetable intake, beef intake, milk intake, inhalation rate, exposure duration, and body weight.

5.2.2 Contaminant Fate and Transport Modeling

The contaminant fate and transport models used in this analysis are the soil partitioning model (Jury et al., 1983, 1984, 1990), to determine contaminant concentrations in the soil; the air emissions model (AP-42) and the air dispersion and deposition model (Industrial Source Complex [ISC3]), to estimate risks from the air pathway; the soil erosion model (universal soil loss equation [USLE]), to estimate risks from surface water; and the indirect exposure model, to estimate exposure point concentrations in the food chain. The Integrated Exposure Uptake Biokinetic (IEUBK) Model (U.S. Environmental Protection Agency [EPA], 1994d) is used to predict blood lead levels in children due to incidental ingestion of fertilizer, ingestion of fertilizer-amended soil, and ingestion of plant and animal products that may contain hazardous constituents as a result of fertilizer use.

5.2.2.1 Air Modeling. The risks via air pathways from exposures to fertilizer applied to agricultural fields are assumed to be (1) direct inhalation of vapors and particles by the farmer and his/her child, (2) wet and dry deposition of particles and vapors to plants, (3) vapor uptake by plants, and (4) air dispersion and deposition of particles and vapors to surface waterbodies. Estimates for exposure by air pathways were obtained by modeling the air concentration of constituents and the deposition to surfaces of plants grown on the amended agricultural field and/or to surface waterbodies.

5.2.2.1.1 *AP-42 Model for Particulate Emissions*. Constituents of fertilizers may be released into the air from the agricultural field by volatilization or by emission of particulate matter (PM). For this analysis, volatile emissions from the agricultural field are estimated using the soil partitioning model presented in Section 5.2.2.2. Particulate emissions are estimated from two types of releases: emissions due to wind erosion and emissions due to agricultural tilling. Releases of both particulate and volatile emissions are limited to releases from the agricultural field. Emissions from other potential sources (such as storing, transporting, loading, and unloading the fertilizer at the farm) are not included because exposures from these short-term activities are expected to be insignificant compared to continuous releases from the agricultural field due to wind erosion and periodic tilling.

Particulate emissions due to wind erosion are modeled using the assumption that the agricultural field is not covered by continuous vegetation or snow and that the surface soil has an unlimited reservoir of erodible surface particles. Factors for estimating emission of particles due to wind erosion and tilling are estimated using methods and equations from EPA's *Compilation of Air Pollution Emissions Factors,* commonly referred to as AP-42 (U.S. EPA, 1985b). These emission factors relate the quantity of a pollutant released to the atmosphere with an activity associated with the release (for example, releases of soil particles through wind erosion of an agricultural field). The equations used to estimate emission factors as provided in AP-42 are presented here.

Equation for Emission of Respirable Particulate Matter:

$$E_{wind} = 0.036 \bullet (1 - V) \bullet \left(\frac{u}{u_t} \right)^3 \bullet f(x) \qquad (5\text{-}1)$$

where

E_{wind} = emissions of PM_{10} (respirable particulate matter) from wind erosion ($g/m^2/s$)
V = vegetative cover (fraction)
u = mean wind speed (m/s)
u_t = threshold wind speed (m/s)
$f(x)$ = function of roughness height.

This empirical equation estimates only the emission of respirable particulate matter (PM_{10}) from the site and is not applicable for the emission of larger particles. Thus, emission of larger particles is not included in the wind erosion equation (Cowherd et al., 1985).

Equation for Emission from Agricultural Tilling:

During agricultural tilling, particulate matter created from loosening and pulverizing the soil is released into the atmosphere as the soil is dropped to the surface. The emission factor used to estimate tilling emissions in this analysis is based on the equation presented in U.S. EPA (1985b):

$$E_{at} = 5.38 \bullet K_{at} \bullet S^{0.6} \bullet N_{op} \bullet CF \qquad (5\text{-}2)$$

where

E_{at} = emissions of soil (PM_{10} or PM_{30}) from agricultural tilling ($g/m^2/s$)
K_{at} = particle size multiplier to adjust results to PM_{10} or PM_{30} (unitless)
S = silt content of soil (%)
N_{op} = number of days of operations (d)
CF = conversion factor ($[d \bullet g \bullet ha]/[s \bullet kg \bullet m^2]$).

Number of Days of Operations (N_{OP}). For estimation of inhalation risk, it is assumed that the fertilizer-amended agricultural field is tilled for 16 days distributed throughout the year for nonmicronutrient fertilizers. Tilling duration may vary up to an order of magnitude from this value (California Department of Food and Agriculture [CDFA], 1998). For micronutrient fertilizers, it is assumed that the field is tilled for 8 days distributed throughout the year (The Fertilizer Institute [TFI], 1999).

Silt Content of Soil (S). The silt content of soil may vary from 3 percent for sandy soil to 87 percent for silty soil. The silt content of agricultural soils considered in this analysis was obtained from the continental United States (CONUS) database. This database presents the silt content for the 11 layers of subsurface (0 to 25 m) for each MUID. In this project, the average silt content of the top 20 cm of soil was calculated for each MUID within a climate region having agricultural land use. This average silt content was input into the AP-42 equations for estimating the particle emissions for that MUID. Table 5-1 shows the representative percentage of silt for each soil texture classification.

Table 5-1. Silt Content of Soils by Soil Texture Classification

Soil Texture Classification	Silt Content (%)
Sand	3
Loamy sand	12
Sandy loam	25
Loam	40
Silty loam	63
Silt	87
Sandy clay loam	14
Clay loam	36
Silty clay loam	58
Sandy clay	8
Silty clay	47
Clay	15

5.2.2.1.2 *ISCST3 Model for Air Dispersion and Deposition*. Air dispersion and deposition modeling is used to estimate the initial fate and transport of vapor and particle emissions in the environment. Air dispersion modeling is conducted with the EPA Industrial Source Complex Short Term, Version 3 (ISCST3) model (1994b). The ISCST3 model is used to estimate the following:

air concentration of vapors,
wet deposition of vapors,
air concentration of particles,
wet deposition of particles, and
dry deposition of particles.

These outputs are used in the estimation of risk from direct inhalation and in the indirect modeling process to develop relative estimates of risks from on-site exposures attributable to emissions from an agricultural field. The ISCST3 model and meteorological preprocessor, PCRAMMET, and related user's guides can be accessed and downloaded through the Internet from the Support Center for Regulatory Air Models (SCRAM) Webpage (http://www.epa.gov/scram001). SCRAM is part of EPA's Office of Air Quality Planning and Standards (OAQPS) Technology Transfer Network (TTN).

5.2.2.1.2.1 ISCST3 Input Files. Two input files are required to run ISCST3: the control file and the meteorological file. The control file contains the model option settings, source parameters, and receptor locations. The control file is divided into five control file sections, or pathways, as described here. The meteorological file contains hourly values of wind speed, wind direction, stability class, mixing height, ambient air temperature, and precipitation type and amount.

Control File

ISCST3 requires site-specific inputs for source parameters, receptor locations, meteorological data, and, in some cases, terrain features. These data are input into the model using a control file. Control file pathways from which the required data are accessed are shown in Table 5-2. Each of the control file pathways and their specifications for this analysis are described here. The *ISC3 User's Guide* (U.S. EPA, 1994b) provides detailed guidance for preparing control files.

Control Pathway

Under the control pathway, the user specifies keywords that determine whether the model will calculate air concentrations or deposition rates as well as the type of model output desired. For this analysis, the desired outputs for the vapor phase included air concentration and wet deposition, and the desired outputs for the particle phase included air concentration, wet deposition, and dry deposition. Combined deposition rates are also required as input to the indirect exposure modeling process, but they were not calculated by ISCST3. Instead, these rates were estimated by externally summing the wet and dry deposition rates as described in Section 5.2.2.1.2.2.

Table 5-2. ISCST3 Control File Pathways

Pathways	Identifier	Use
Control options	CO	Provides overall control of the model run (e.g., modeling options are selected)
Source characteristics	SO	Defines emission source information for the model run
Receptor locations	RE	Defines receptor information for the model run
Meteorological data	ME	Defines the meteorological data for the model run
Terrain file	TG	Defines the input terrain information for the model run
Output options	OU	Defines output options for the model run

Source: *Guidance for Performing Screening Level Risk Analyses at Combustion Facilities Burning Hazardous Wastes* (U.S. EPA, 1994).

ISCST3 is a Gaussian plume model that can simulate plume depletion. For this analysis, the wet plume depletion option was activated and used to calculate outputs for both vapors and particles. The dry plume depletion modeling option, however, was not used in this analysis because the run times associated with dry plume depletion are excessive (i.e., preliminary model runs for particles indicate that use of the dry plume depletion option significantly increased run times for a large area source from 1 day to approximately 2 weeks). Review of data obtained for prior runs conducted with dry plume depletion for particles and those without indicate that air concentrations and dry deposition rates, respectively, are two and six times higher when dry plume depletion is not calculated (see Appendix H). Consequently, exclusion of dry plume depletion for this analysis resulted in higher estimates of particle deposition and, therefore, higher risk.

Another modeling option is whether to run the simulation in rural or urban mode. This distinction is based on the land use within a 3-km radius from the emission source. These modes differ based on the wind profile exponent and temperature gradient. Unless the site is located in a heavily metropolitan area, the rural option is generally more appropriate. Because the types of agricultural fields being assessed are typically in nonurban areas, the rural option was used in this analysis.

Source Characteristics Pathway

Under the source characteristics pathway, the user provides information to characterize the emission source being modeled.

For this analysis, the source type specified was a square-shaped area (i.e., an agricultural field). In the absence of site-specific information, a square source with sides parallel to selected x- and y-axes was modeled. For this analysis, the x- and y-coordinates of the southwest corner of the source were specified as (-870,-870) for a field size of 1,740 m x 1,740 m. The size of the agriculture field modeled was determined from farm size data obtained from the Agricultural Census (Government Information Sharing Project, Oregon State University, Information Services Census of Agriculture: 1982, 1987, 1992; available online at http://govinfo.kerr.orst.edu/ag-stateis.html). The selected field, 1,740 m x 1,740 m, represents the 90th percentile-sized farm as described in Section 4.2.7. Variation in field sizes was addressed through a sensitivity analysis (Appendix H). The time required to provide dispersion modeling results to be used as Monte Carlo distribution inputs to the indirect modeling would have exceeded the total duration of this work assignment. Therefore, a single-sized farm was chosen as a conservative assumption for modeling, and the variation was addressed through a sensitivity analysis.

A sensitivity analysis was conducted to ensure that the selected field size resulted in protective estimates of air deposition. Modeling was conducted for four additional field sizes identified from Agricultural Census data. The field sizes included were 350 m x 350 m (25th percentile), 700 m x 700 m (50th percentile), 1,240 m x 1,240 m (80th percentile), and 2,460 m x 2,460 m (95th percentile). ISCST3 modeling was completed for each of these field sizes using meteorological data from a subset of four meteorological stations. These four stations were selected based on an analysis of the combined deposition rates for particles obtained for the 29 meteorological sites described previously. The four stations were Hartford, CT; Fresno, CA;

Minneapolis, MN; and Atlanta, GA. These sites were associated with the 25th, 50th, 75th, and 95th percentile combined deposition rates, respectively. Combined deposition of particles, which is driven by the dry deposition rates in all 29 cases, is important to this analysis because the majority of the constituents of concern are typically associated with particles that will deposit on plants, soil, and water. Appendix H presents the air modeling sensitivity analysis results obtained for each of the fields. These results indicate that the agricultural field modeled for this assessment (1,740 m x 1,740 m) is associated with protectively high air modeling results.

The source-specific dimensions required as input for an area source include

- Relght – Release height above ground in meters (set equal to 0),
- Xinit – Length of x dimension of the area in meters (set equal to 1,740 m),
- Yinit – Length of y dimension of the area in meters (set equal to 1,740 m), and
- Angle – Orientation angle (set equal to 0).

Particle size distributions and scavenging coefficients are input into the particle control file while gas scavenging coefficients are input into the vapor control file. Table 5-3 identifies the particle size distribution and the associated scavenging coefficients that were applied for particles. The scavenging coefficients associated with the particle size distribution shown were obtained from Jindal and Reinhold (1991). Liquid and frozen scavenging coefficients are set equal (PEI, 1986). A vapor scavenging coefficient of 1.7E-4 (h/mm-s) is assumed and input into the vapor control file. Although wet scavenging of vapors depends on the properties of the chemicals involved, not enough data are available now to develop chemical-specific scavenging coefficients adequately. Therefore, gases are assumed to be scavenged at the rate of small particles whose behavior in the atmosphere is assumed to be influenced more by the molecular processes that affect gases than the physical processes that often dominate the behavior of larger particles. The value 1.7E-4 (h/mm-s) for the gas scavenging coefficient was also taken from Jindal and Reinhold (1991). A scavaging ratio approach was used to model the deposition of gases and particles through wet removal. The coefficients used in this analysis are based on mean particle size values.

Table 5-3. Particle Size Distribution and Scavenging Coefficients

Particle Size Diameter (µm)	Weight Distribution (Fraction)	Liquid and Frozen Scavenging Coefficients (h/mm-s)
range 0 to 10 mean 5.0	0.50	3.7E-4
range 10 to 30 mean 20	0.50	6.7E-4

To estimate on-site impacts for this assessment, 121 receptors are evenly spaced across the field. Dispersion modeling is conducted using data from 29 representative meteorological locations. The ISCST3 model outputs were averaged across the field receptors. The average concentrations and deposition rates obtained for each meteorological location are used as input to the indirect modeling process. The air modeling results from this effort are presented in Appendix H.

Receptor Pathway

To ensure that a sufficient number of receptors were considered for this analysis, additional modeling was conducted using 16 receptors and 441 receptors evenly spaced across the field. Results obtained as output were compared with those obtained using the 121 receptors. As shown in Appendix H, the difference between the results obtained with the 121 receptors and those obtained with the 441 receptors is insignificant. This indicates that points of maximum impact are not neglected by the reduction in the number of receptors. Therefore, it appears that the results obtained by modeling the 121 receptors are sufficient to characterize average impacts across the field.

The elevation at each receptor can also be input when it is necessary to consider terrain (intermediate or complex) at a location. Because the field modeled as part of this analysis is assumed to be a flat ground-based source, it was not necessary to provide terrain data.

Meteorological Pathway

For this assessment, modeling is conducted using data obtained from 29 representative meteorological stations. As previously described, these stations were selected based on an assessment conducted for EPA’s Superfund soil screening level (SSL) program (Environmental Quality Management [EQM], 1993) as being representative of the nine general climate regions of CONUS. To characterize long-term impacts, 5 years of meteorological data are needed as input from each of the 29 meteorological stations. Sufficient data were available for all but 3 of the 29 meteorological locations: Denver, CO; Lincoln, NE; and Little Rock, AR. In the absence of adequate data for these three sites, these alternate locations were selected based on proximity and similar weather conditions: Boulder, CO; Grand Island, NE; and Memphis, TN. A list of all 29 meteorological stations included in this analysis is provided in Table 5-4.

Terrain Pathway

The terrain pathway, optional for the Industrial Source Complex (ISC) models, was omitted from this analysis because the terrain surrounding the source is assumed to be flat.

Output Pathway

ISCST3 results can be generated in several different formats. For example, a table of maximum values or a table of values for each receptor can be generated. For this analysis, plotter output files are specified to facilitate averaging across field receptors. The plotter files list the

Table 5-4. Meteorological Stations Selected for Analysis

Meteorological Locations	
Albuquerque, NM	Los Angeles, CA
Atlanta, GA	Memphis, TN
Bismark, ND	Las Vegas, NV
Boise, ID	Miami, FL
Boulder, CO	Minneapolis, MN
Casper, WY	Philadelphia, PA
Chicago, IL	Phoenix, AZ
Charleston, SC	Portland, ME
Cleveland, OH	Raleigh-Durham, NC
Fresno, CA	Seattle, WA
Grand Island, NE	San Francisco, CA
Harrisburg, PA	Salt Lake City, UT
Hartford, CT	Salem, OR
Houston, TX	Winnemucca, NV
Huntington, WV	

x- and y-coordinates of all the modeled receptors and their corresponding air concentrations and deposition rates.

Meteorological File

The meteorological file is generated using the meteorological preprocessor PCRAMMET. This preprocessor pairs hourly surface observations with upper air soundings. The preprocessor creates a file that contains hourly wind speed, wind direction, atmospheric stability class, temperature, and mixing height.

For each location modeled, 5 years of surface and upper air data were obtained to

Key Meteorological Data for the ISCST3 Model

Wind Direction: Determines the direction of the greatest impact.

Wind speed: Ground-level air concentration is inversely proportional to wind speed, so the lower the wind speed, the higher the concentration.

Stability Class: Impacts rate of lateral and vertical diffusion. The more unstable the air, the greater the diffusion.

Mixing Height: Determines the height to which the constituent can be diffused vertically.

determine long-term average air dispersion and deposition estimates. Surface data were obtained from the Solar and Meteorological Surface Observation Network (SAMSON) on CD-ROM (National Oceanic and Atmospheric Administration [NOAA], 1993). These data include 5 years of hourly observations of the following meteorological parameters: opaque cloud cover, temperature, wind direction, wind speed, ceiling height, current weather, station pressure, and precipitation type and amount. In addition, daily precipitation amounts were obtained from the Cooperative Summary of the Day on CD-ROM[1]. These data were used to ensure that the hourly precipitation data obtained from SAMSON did not underestimate actual precipitation amounts. The corresponding upper air data (i.e., twice daily mixing height data) were obtained from EPA's SCRAM.

In processing the meteorological data, the model requires additional inputs for the modeled site and meteorological station. These input parameters included anthropogenic heat flux, bowen ratio, minimum Monin-Obukhov length, noontime albedo, fraction of net radiation absorbed by the ground, and surface roughness length. In the absence of field-specific information for these inputs, conditions at the modeled sited are assumed to be similar to those at the meteorological station. Therefore, the inputs for the site are set equal to those developed for the meteorological station. The inputs were developed for each meteorological location based on guidance and default values provided in the PCRAMMET user’s guide and from Geographic Information Retrieval and Analysis System (GIRAS) data. GIRAS provides comprehensive land use data in digital GIS format. Anemometer heights were obtained from the Local Climatological Data, Annual Summaries.

5.2.2.1.2.2 ***Estimating Chemical-Specific Air Concentrations and Deposition Rates***. To reflect the vapor-particle split of emissions, air dispersion modeling is performed separately for the vapor phase and the particle-bound phase. The ISCST3 outputs obtained for vapors included air concentration and wet deposition. Dry deposition of vapors is calculated from the air concentration of vapors and an assumed deposition rate for vapors (0.2 cm/s)[2]. Outputs obtained for particles included wet deposition of particles, dry deposition of particles, and air concentration of particles. The combined deposition rate of particles is estimated by summing the results obtained for the dry and wet deposition of particles.

Each phase is modeled using a unit emission rate of 1 $\mu g/m^2$-s to obtain unitized air concentrations and deposition rates. The unitized air modeling results are converted to chemical-specific air concentrations and deposition rates for the exposure analysis. This conversion, shown

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[1] An analysis that compared long-term averages calculated based on the SAMSON hourly precipitation data to long-term values from the International Station Meteorological Climate Summaries (ISMCS) revealed that the SAMSON data significantly underestimated long-term precipitation amounts. Consequently, adjustments to the hourly data were made based on the daily precipitation amounts obtained from the Cooperative Summary of the Day on CD-ROM.

[2] Dry deposition of vapors was needed as input to the indirect modeling, but this output could not be calculated using the current version of ISCST3 (dated 12/28/98). Dry deposition of vapors must be calculated as the product of vapor air concentration times an assumed dry deposition velocity (0.2 cm/s). Dry deposition of vapors, however, was very small and not expected to significantly influence modeling results.

here, accounts for chemical-specific emission rates (Q) and the partitioning of chemicals between the vapor and particle phases.

Vapor Phase

All vapor-phase air model outputs (i.e., air concentration and wet deposition) are multiplied by the fraction of the compound in the vapor phase (fv) and the emission rate (Q) as follows:

$$\text{Vapor}-\text{phase air conc.} = \frac{\text{Unitized Air Conc. of Vapor x Chemical}-\text{Specific Emissions x fv}}{\text{Unit Emission Rate}} \tag{5-3}$$

$$\text{Vapor}-\text{phase wet deposition} = \frac{\text{Unitized Wet Dep. of Vapor x Chemical}-\text{Specific Emission x fv}}{\text{Unit Emission Rate}} \tag{5-4}$$

Particle Phase

Similarly, all particle-bound air model outputs are multiplied by the fraction of emissions in the particle phase (1-fv) and the emission rate (Q).

$$\text{Particle}-\text{phase air conc.} = \frac{\text{Unitized Air Conc. of Particles x Chemical}-\text{Specific Emission x }(1-\text{fv})}{\text{Unit Emission Rate}} \tag{5-5}$$

For each compound, the particle-phase combined deposition (Equation 5-8) is estimated by summing the chemical-specific particle-phase wet deposition and the particle-phase dry deposition values.

$$\text{Particle}-\text{phase dry deposition} = \frac{\text{Unitized Dry Dep. of Particles x Chemical}-\text{Specific Emission x }(1-\text{fv})}{\text{Unit Emission Rate}} \tag{5-6}$$

$$\text{Particle}-\text{phase wet deposition} = \frac{\text{Unitized Wet Dep. of Particles x Chemical}-\text{Specific Emission x }(1-\text{fv})}{\text{Unit Emission Rate}} \tag{5-7}$$

$$\text{Particle}-\text{phase combined deposition} = \text{particle}-\text{phase dry deposition} + \text{particle}-\text{phase wet deposition} \tag{5-8}$$

5.2.2.2 <u>Soil Modeling</u>. Soil modeling is conducted to determine the contaminant concentrations in soil after losses from degradation, volatilization, leaching, and rainwater runoff. A spreadsheet calculation model incorporating the Jury equations (Jury et al., 1983, 1984, 1990) is used to estimate soil contaminant concentrations after losses from these routes. Enhancement of the volatilization rate due to convection of water vapor (i.e., evaporation) is also included in the model. The model tracks the average annual soil concentration and the annual mass of contaminant volatilized for a period of 100 years of active use (corresponding to the period over which fertilizer application occurs), followed by 40 years of inactive use.

5.2.2.2.1 ***Total Contaminant Concentration in Soil***. The total concentration of the contaminant in the soil can be expressed as the sum of the masses of the contaminant adsorbed on the soil, dissolved in the aqueous phase, and volatilized in the pore spaces, divided by the total mass of contaminated soil as follows:

$$C_T = C_s + \theta_w C_w/\rho_b + \theta_a C_a/\rho_b \qquad (5\text{-}9)$$

where

C_T = total contaminant concentration (mg/kg=g/Mg)
C_s = concentration of contaminant adsorbed on soil (mg/kg=g/Mg)
θ_w = water-filled soil porosity (m^3_{water}/m^3_{soil})
C_w = concentration of contaminant dissolved in the water ($\mu g/cm^3 = g/m^3$)
ρ_b = soil dry bulk density ($g/cm^3 = Mg/m^3$)
θ_a = air-filled soil porosity (m^3_{air}/m^3_{soil})
C_a = concentration of contaminant in air ($\mu g/cm^3 = g/m^3$).

The adsorbed contaminant concentration is assumed to be linearly related to the aqueous phase concentration as follows:

$$C_s = K_d C_w \qquad (5\text{-}10)$$

where

K_d = soil-water partition coefficient ($cm^3/g = m^3/Mg$) = $K_{oc} f_{oc}$
K_{oc} = soil-organic carbon partition coefficient (cm^3/g)
f_{oc} = fraction of organic carbon content of soil (g/g).

The contaminant concentration in the vapor phase is assumed to be linearly related to the aqueous phase concentration as follows:

$$C_a = H' C_w \qquad (5\text{-}11)$$

where

H' = dimensionless Henry's law constant = 41×H (dimensionless)
H = Henry's law constant at 25 °C ($atm\text{-}m^3/mol$).

Equations (5-10) and (5-11) assume linear equilibrium partitioning between the adsorbed contaminant, the dissolved contaminant, and the volatilized contaminant. Combining Equations (5-9), (5-10), and (5-11) yields the following:

$$C_T = C_s \left[1 + \theta_w/(K_d\rho_b) + \theta_a H'/(K_d\rho_b)\right]. \qquad (5\text{-}12)$$

The total contaminant concentration, C_T, represents the measured soil concentration. The adsorbed soil concentration, C_s, however, is used to calculate the equilibrium partitioning between the air, water (runoff), and soil phases. Equation (5-11) can be rearranged to calculate the adsorbed soil contaminant concentration given the total contaminant concentration as follows:

$$C_s = C_T\, K_d\, \rho_b / (K_d\, \rho_b + \theta_w + \theta_a\, H'). \tag{5-13}$$

The total mass of contaminant applied to the soil during the first annual application can be calculated as follows:

$$M_{s,app} = (C_T\, Q_{app}) \times 1\text{yr} \tag{5-14}$$

where

$M_{s,app}$ = mass of contaminant in soil from fertilizer application (g)
Q_{app} = annual fertilizer application rate (Mg/yr).

5.2.2.2.2 ***Contaminant Loss Through Degradation***. Contaminant loss through degradation is estimated from contaminant half-lives in soil. Contaminant loss to the air, to rainwater runoff, or to leachate is calculated from the mass flux of contaminant across the boundaries of the agricultural field. A mass balance around the agricultural field can be written as follows:

$$M_{s,t+\Delta t} = M_{s,t} - M_{degr,t} - (J_{air,t} + J_{leach,t} + J_{runoff,t})(A\Delta t) \tag{5-15}$$

where

$M_{s,t+\Delta t}$ = mass of contaminant in soil at time $t+\Delta t$ (g)
$M_{s,t}$ = mass of contaminant in soil at time t (g)
$M_{degr,t}$ = mass of contaminant degraded at time t (g)
$J_{air,t}$ = contaminant flux to the atmosphere at time t (g/m^2-s)
$J_{leach,t}$ = contaminant flux in leachate at time t (g/m^2-s)
$J_{runoff,t}$ = contaminant runoff rate at time t (g/m^2-s)
A = area of agricultural field (m^2)
Δt = time step of calculation (s).

Reported values for contaminant half-life in soil, expressed in terms of a first-order rate constant, are used to calculate the total contaminant loss from the system in a given time step as follows:

$$\Delta M_{half} = M_{s,t}\, [1 - \exp(k_{half})] \tag{5-16}$$

where

ΔM_{half} = expected mass of contaminant loss from half-time data (g)
k_{half} = first-order rate constant based on contaminant half-life in soil (per s).

If the amount of contaminant loss through leaching, runoff, and volatilization exceeds the expected mass loss from the half-life data, then the mass degraded is set to 0. Otherwise, the mass degraded is calculated from the expected mass loss and the predicted leaching, runoff, and volatilization losses as follows:

If $\Delta M_{half} < (J_{air,t} + J_{leach,t} + J_{runoff,t})\,(A\Delta t)$, (5-17)
then: $M_{degr,t} = 0$.

Otherwise: $M_{degr,t} = \Delta M_{half} - (J_{air,t} + J_{leach,t} + J_{runoff,t})\,(A\Delta t)$. (5-18)

After each time step, which is approximately 1 week in duration, the mass of contaminant remaining in the soil is calculated. The contaminant concentrations are assumed to be uniform over the tilling depth starting with each new time step. That is, the model does not attempt to assess the concentration profiles (as a function of depth) that can develop over time in the tilled soil. This assumption is reasonable for agricultural fields that are tilled regularly.

5.2.2.2.3 ***Additions of Contaminants to the Soil***. The only mass additions to the system are assumed to occur during fertilizer applications. Because the fertilizer is assumed to be applied over a period of 100 years, some model scenarios can result in substantial depth of fertilizer accumulation relative to the assumed tilling depth. During the application, it is, therefore, assumed that the effective tilling depth of soil and depth of new fertilizer application are equal. Consequently, a thin layer of contaminated soil the depth of which is equal to the depth of fertilizer added during the annual application just below the tilling depth also is assumed. As this thin, buried, contaminated layer is necessarily at a lower concentration than the tilled soil directly above (and beneath the root zone), it is not expected to contribute significantly to the exposure pathway mechanisms (air emissions, surface soil concentration, and leachate concentration). Therefore, the mass of contaminant in this untilled, buried soil layer is essentially lost from the system and was subtracted from the mass of contaminant in the active fertilizer area. Consequently, the net mass of contaminant added to the agricultural field at the start of Year 1 through Year 100 can be calculated as follows:

$$M_{s,app} = C_T\, Q_{app}\, \{1 - [(Q_{app} \times 1\text{-yr})/(A\, \rho_b)]/d_{till}\} \times 1\text{-yr} \tag{5-19}$$

where

d_{till} = tilling depth (m).

This allows the system to reach a steady state. For very persistent constituents, such as metals and dioxins, the constituents initially build up rapidly and may not reach a steady-state concentration for approximately 40 to 50 years.

5.2.2.2.4 ***Volatilization of Contaminants from the Soil to the Atmosphere***. The primary mechanism of contaminant loss to the atmosphere is the diffusion of volatilized contaminant from the soil surface. During periods of evaporation, the flux of water vapor enhances contaminant transport to the soil surface. Consequently, the total contaminant flux to the atmosphere can be calculated as follows:

$$J_{air,t} = J_{vol,t} + J_{evaptr,t} \qquad (5\text{-}20)$$

where

$J_{vol,t}$ = contaminant flux to the atmosphere due to diffusion (g/m^2-s)
$J_{evaptr,t}$ = contaminant flux to the atmosphere due to evaporative transport (g/m^2-s).

Assuming that there is no stagnant boundary air layer at the ground surface, the simplified finite source model for diffusional volatilization (Jury et al., 1990) can be written as follows:

$$J_{vol,t} = C_T\ (0.01D_A/\pi t)^{\frac{1}{2}}\ \{1\text{-}\exp[-d_s^{\,2}/(0.04D_A t)] \qquad (5\text{-}21)$$

where

D_A = apparent diffusivity (cm^2/s)
π = 3.14
t = time (s)
d_s = depth of uniform soil contamination at t=0 (m)

and

$$D_A = [(\theta_a^{\,10/3}\ D_i\ H' + \theta_w^{\,10/3}\ D_w)/n^2]/(\rho_b\ K_d + \theta_w + \theta_a\ H') \qquad (5\text{-}22)$$

where

D_i = diffusivity in air (cm^2/s)
D_w = diffusivity in water (cm^2/s)
n = total soil porosity (L_{pore}/L_{soil}) = 1 - (ρ_b/ρ_s)
ρ_s = soil particle density (g/cm^3).

As discussed in Jury et al. (1984), volatilization with evaporation is a complex problem, but evaporation always increases the overall volatilization rate. Jury et al. (1984) present an equation for the convection of contaminants caused by the flux of water in the soil. The convective volatilization flux caused by evaporation is then calculated by isolating the first half of the overall volatilization flux equation (Jury et al., 1983), which can be written as follows:

$$J_{evaptr,t} = \tfrac{1}{2}\ C_T\ \rho_b\ (0.01V_E)\ \{\mathrm{erfc}[V_E\ t/(4\ D_A\ t)\tfrac{1}{2}] - \mathrm{erfc}[(100d_s + V_E\ t)/(4\ D_A\ t)^{\frac{1}{2}}]\} \qquad (5\text{-}23)$$

where

V_E = evaporative convective velocity (cm/s)
erfc(x) = complementary error function

and

$$V_E = [E/(365 \times 24 \times 3600]/(\rho_b K_d + \theta_w + \theta_a H') \qquad (5\text{-}24)$$

where

E = average annual evaporation rate (cm/yr).

5.2.2.2.5 ***Leaching of Contaminants from the Soil to the Groundwater***. The mass flux loss of a contaminant due to leaching is estimated by assuming the leachate is in equilibrium with the soil (i.e., Equation 5-10 applies), as follows:

$$J_{leach,t} = C_T \rho_b (0.01V_L)/(\rho_b K_d + \theta_w + \theta_a H') \qquad (5\text{-}25)$$

where

V_L = (P + I - R - E)/(365 × 24 × 3,600] = leachate rate (cm/s)
P = annual average precipitation rate (cm/yr)
I = annual average irrigation rate (cm/yr)
R = annual average runoff rate (cm/yr).

5.2.2.2.6 ***Runoff of Contaminants from the Soil to the Surface Water***. The equation describing the mass flux loss of a contaminant due to runoff is nearly identical to Equation 5-25, because the runoff is also assumed to be in equilibrium with the contaminated soil. Consequently, the total mass rate of contaminant loss due to runoff can be calculated as follows:

$$J_{runoff,t} = C_T \rho_b (0.01V_R)/(\rho_b K_d + \theta_w + \theta_a H') \qquad (5\text{-}26)$$

where

$$V_R = R/(365 \times 24 \times 3{,}600] = \text{runoff rate (cm/s)}. \qquad (5\text{-}27)$$

The results of the Jury et al. equations yield the effective average soil concentration and vapor concentration for individual constituents for the exposure periods.

5.2.2.2.7 ***Assumptions***. The Jury et al. modeling incorporates several basic simplifying assumptions. Some of the more significant assumptions and limitations are as follows:

The adsorbed contaminant concentration is assumed to be linearly related to the aqueous-phase concentration.

- # The contaminant concentration in the vapor phase is assumed to be linearly related to the aqueous-phase concentration.

- # The only mass additions to the system occur during fertilizer applications.

- # The contaminant concentrations are assumed to be uniform over the tilling depth.

- # There is a thin layer of untilled contaminated soil (the depth equal to the depth of fertilizer added during the annual application) just below the tilling depth. As this layer is buried, it is lost from the system and not expected to contribute significantly to the exposure pathways.

The parameters in this model that are varied in the Monte Carlo analysis are presented in Table 5-5. This table shows the parameters that are varied and the larger group of variables to which each parameter is linked (e.g., product-specific).

Table 5-5. Parameters Varied in the Soil Partitioning Model

Parameter	**Parameter Grouping**
Constituent concentration	Product-specific
Application rate	Product-specific
Annual precipitation	Climate region-specific
Annual irrigation	Climate region-specific
Annual evapotranspiration	Climate region-specific
Annual runoff	Climate region-specific
Annual infiltration	Climate region-specific
Soil water porosity	Climate region-specific
Soil air porosity	Climate region-specific
Soil total porosity	Climate region-specific
K_d	Constituent-specific

5.2.2.3 <u>Surface Water Modeling</u>. This analysis includes estimates of risk from the ingestion of fish taken from waterbodies adjacent to fields amended with fertilizer. For this analysis, the waterbody is assumed to be a stream adjacent to the agricultural field to which fertilizer has been applied. Constituents in fertilizers can reach the stream from the agricultural field through soil erosion or wind deposition. Windblown deposition is conservatively estimated to be equal to on-site deposition. Soil erosion from the agricultural field to the adjacent waterbody is modeled using the integrated setting approach (Beaulieu et al., 1996) developed for the petroleum refinery listing decision's nongroundwater risk analysis and presented in *Background Document; Nongroundwater Pathway Risk Assessment; Petroleum Process Waste*

Listing Determination (U.S. EPA, 1997d). See Figure 5-1 for a diagram of the integrated setting used in this analysis.

5.2.2.3.1 ***Soil Erosion***. The method of estimating risk from the overland transport pathways was modified by EPA's Office of Solid Waste (OSW) and Office of Research and Development (ORD). The USLE was modified to estimate soil erosion and overland transport of sediment from agricultural fields across intervening areas to nearby waterbodies by evaluating this process in an integrated setting (Beaulieu et al., 1996). These modified USLE equations were used for this analysis.

For this analysis, the area, including the agricultural field and the intervening area, is considered to be an independent drainage sub-basin. The soil erosion load from the sub-basin to the waterbody was estimated using a distance-based sediment delivery ratio, and the sediment not reaching the waterbody was assumed to be deposited evenly over the area of the sub-basin. Thus, using mass balance equations, contributions to the constituent concentrations of the waterbody and of the soil can be estimated. The equations implementing the concept of the integrated setting are based on the following assumptions:

The area of the agricultural field and the area between the field and the nearest waterbody make up a discrete drainage sub-basin. This area is shown in Figure 5-1.

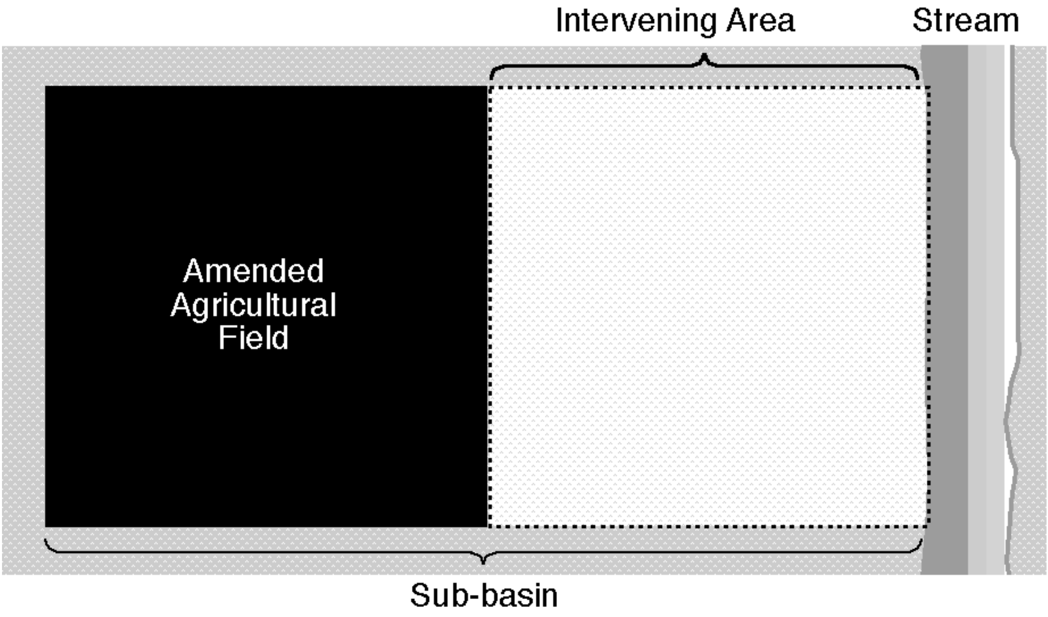

Figure 5-1. Diagram of integrated soil erosion setting.

- The sediment delivery ratio (SD_{SB}) and the soil loss rate per unit area are assumed to be constant for all areas within the sub-basin.

- The amount of soil deposited onto the intervening area through soil erosion was estimated by assuming that the fraction of soil that did not reach the waterbody remains in the sub-basin.

- The entire sub-basin drainage system is assumed to be at steady state. Consequently, steady-state soil concentrations for the different subareas (e.g., surrounding area) can be calculated using a mass balance approach.

- The soils within the watershed are assumed (on average) to have the same soil properties (e.g., bulk density, soil moisture content), a reasonable assumption for areas with similar irrigation rates with infrequent tilling.

- The soil/constituent movement within the entire watershed was evaluated separately from the soil/constituent movement that occurs in the drainage sub-basin. Only air deposition of constituents contribute to the constituent concentrations in soil outside the sub-basin. The contribution of each area within the watershed to the constituent concentration in the waterbody was estimated independently and summed to estimate the total waterbody concentration.

- No contributions to constituent concentrations are assumed to occur from sources other than the agricultural field within the sub-basin.

The values for the soil erosion setting are presented in Appendix I with the equations in which they were used.

5.2.2.3.2 ***Constituent Load to Waterbody***. The total load to the waterbody (L_T) is the sum of the constituent load via erosion (L_E) and the constituent load from pervious runoff (L_R). The total load to the waterbody was used to estimate the risk to the subsistence and/or recreational fisher from the ingestion of fish. The estimation of L_E required the calculation of a weighted average constituent concentration in watershed soil based on the eroded soil contribution ($S_{c,erode}$), and the L_R term required the calculation of a weighted average constituent concentration based on the pervious runoff contribution ($S_{c,run}$). The weighted average constituent concentration represents the effective watershed soil concentration based on contributions from the sub-basin and the remainder of the watershed. Most important, the weighted average concentration accounts for the differences in constituent concentrations in the different areas within the watershed. The calculation of L_T required constituent concentrations to be calculated for each of the following areas within the watershed: the source, the buffer and the surrounding area, and the watershed area outside the drainage sub-basin. For the watershed soil outside the sub-basin, it is assumed that constituents reach the watershed solely by air deposition (i.e., no erosion component).

If the erosion load (L_E) to the surface waterbody for each of these areas is considered individually, the equation can be written as follows:

$$
\begin{aligned}
L_E = \; & [X_{e,SB} \times ER \times SD_{SB} \times A_0 \times C_0 \times (\frac{Kd_s\ BD}{\theta + Kd_s\ BD}) \times 0.001] \\
& + [X_{e,SB} \times ER \times SD_{SB} \times (\frac{Kd_s\ BD}{\theta + Kd_s\ BD}) \times 0.001] \\
& + [X_{e,SB} \times ER \times SD_{SB} \times A_{B/Surr} \times C_{B/Surr} \times (\frac{Kd_s\ BD}{\theta + Kd_s\ BD}) \times 0.001] \\
& + [X_e \times ER \times SD_{WS} \times [A_{WS} - (A_0 + A_{B/Surr})] \times C_{WS} \times (\frac{Kd_s\ BD}{\theta + Kd_s\ BD}) \times 0.00
\end{aligned}
\tag{5-27}
$$

where

L_E = constituent load to watershed due to erosion (g/yr)
$X_{e,SB}$ = unit soil loss in sub-basin (kg/m^2/yr)
ER = enrichment ratio
SD_{SB} = sediment delivery ratio for sub-basin
A_0 = area of source (m^2)
C_0 = constituent concentration at the source (mg/kg)
BD = soil bulk density (g/cm^3)
Kd_s = soil-water partition coefficient (L/kg) or (cm^3/g)
$A_{B/Surr}$ = area of buffer and surrounding area (m^2)
$C_{B/Surr}$ = constituent concentration in buffer and surrounding area (mg/kg)
X_e = unit soil loss in watershed outside of sub-basin (kg/m^2/yr)
SD_{WS} = sediment delivery ratio for watershed (unitless)
A_{WS} = area of entire watershed (m^2)
C_{WS} = constituent concentration in watershed soil outside sub-basin (mg/kg).

The enrichment ratio (ER) was included in the revised soil erosion equations. This factor represents the reality that erosion favors the lighter soil particles, which have higher surface-area-to-volume ratios and higher organic matter content. Therefore, concentrations of organic constituents, which are a function of the organic carbon content of the sorbing media, are expected to be higher in eroded soil than in in situ soil. This factor is generally assigned values in the range of 1 to 5. A value of 3 for organic contaminants and a value of 1 for metals are reasonable first estimates and were used in this analysis (U.S. EPA, 1993a).

Alternatively, this equation can be written in terms of an average weighted soil concentration for the watershed that results in the same constituent load as a function of erosion and sediment delivery. The $S_{c,erode}$ term shown at the end of Equation 5-28 reflects this modification, as follows:

$$
L_E = [X_e \times ER \times SD_{WS} \times A_{WS} \times (\frac{Kd_s\ BD}{\theta + Kd_s\ BD}) \times 0.001] \times S_{c,erode}. \tag{5-28}
$$

Setting L_R equal to each other in the previous two equations and solving for $S_{c,erode}$ yields the following:

$$S_{c,erode} = \frac{(X_{e,SB} \times A_s \times C_0 \times SD_{SB}) + (X_{e,SB} \times A_{B/Surr} \times C_{B/Surr} \times SD_{SB}) + (X_{e,SB} \times SD_{SB})}{X_e \times SD_{WS} \times A_{WS}} + \frac{\{[A_{WS} - (A_0 + A_{B/Surr})] \times C_{WS}\}}{A_{WS}} \qquad (5\text{-}29)$$

where

$S_{c,erode}$ = l
A_s = l
SD_{SB} = l.

Equation 5-30 accounts for differences in the sediment delivery ratios (SD), surface areas (A), and mixing depths (Z) for discrete areas of the watershed (i.e., source, receptor field, buffer/surrounding areas, and remaining watershed). Similarly, the weighted average for runoff losses (ksr) is derived using the areas for various watershed components (e.g., receptor site field, watershed outside drainage sub-basin); however, different sediment delivery ratios are not required because soil in the area is considered to be similar and the slope is considered uniform. It is possible to generate simple area-based weighting factors because the rainfall runoff per unit area is assumed to be constant for the entire watershed area.

The total load to the waterbody (L_T) also requires the constituent load from pervious runoff (L_R). The L_R term is calculated using Equation 5-29, as follows:

$$L_R = R \times (A_{ws} - A_I) \times \frac{S_c \times BD}{\theta + Kd_s \times BD} \times 0.01 \qquad (5\text{-}30)$$

where

L_R = pervious surface runoff load (g/yr)

R = average annual surface runoff (cm/yr)

A_{ws} = area of entire watershed (m^2)

A_I = impervious watershed area receiving constituent deposition (m^2)

S_c = weighted average constituent concentration in total watershed soil (watershed and sub-basin) based on surface area (mg/kg)

BD = soil bulk density (g/cm^3)

θ = volumetric soil content of soil (cm^3/cm^3)

Kd_s = soil-water partition coefficient (L/kg) or (cm^3/g)

0.01 = units conversion factor ($kg\text{-}cm^2/mg\text{-}m^2$).

Assuming that the ratio of pervious soil to impervious soil is the same for each of the designated areas, a correction for areas that do not erode (streets, rocks, and so on) can be added to Equation 5-28 by replacing A_{WS} with $A_{WS} - A_I$, where A_I equals the total impervious area in the watershed.

5.2.2.3.3 ***Constituent Concentrations Throughout the Watershed Area***. The constituent concentrations for the buffer and surrounding area ($C_{B/Surr}$) and the watershed area outside of the drainage sub-basin (C_{WS}) are required to solve $S_{c,erode}$. As suggested previously, a mass balance approach was used to calculate the constituent concentrations for all watershed components.

The concentration in the buffer and surrounding area can be calculated as follows:

$$M_{B/Surr}(dC_{B/Surr} / dt) = (SL_{0,B/surr}\ C_0) + [M_{B/Surr}\ (Ds_{(1),B/Surr} - ks_{B/Surr}\ C_{B/Surr})] \qquad (5\text{-}31)$$

where

$M_{B/Surr}$ = mass of the buffer and surrounding area (kg)
$C_{B/Surr}$ = constituent concentration in the buffer and surrounding area (mg/kg)
$SL_{0,B/Surr}$ = soil load from source to buffer/surrounding areas (kg/yr)
C_0 = soil constituent concentration at the source (mg/kg)
$Ds_{(1),B/Surr}$ = air deposition rate from source to buffer and surrounding area (mg/kg-yr)
$ks_{B/Surr}$ = constituent loss rate coefficient for the buffer/surrounding area (per/yr).

At steady state, this equation may be solved for $C_{B/Surr}$ as follows:

$$C_{B/Surr} = (C_0\ SL_{0,B/Surr} + M_{B/Surr}\ Ds_{(1),B/Surr})/(M_{B/Surr}\ ks_{B/Surr}) \ . \qquad (5\text{-}32)$$

For the watershed soil outside the sub-basin, it is assumed that constituents reach the watershed solely by air deposition (i.e., not through erosion). Using similar mass balance and steady-state assumptions, the constituent concentration in watershed soil outside the sub-basin can be calculated using

$$C_{WS} = Ds_{(1),WS} / ks_{WS} \qquad (5\text{-}33)$$

where

C_{WS} = soil constituent concentration in the watershed (mg/kg)
$Ds_{(1),WS}$ = air deposition rate from source to the watershed (mg/kg/yr)
ks_{WS} = constituent loss rate coefficient for the watershed (per yr).

5.2.2.4 <u>Food Chain Modeling</u>. This analysis also includes estimates of risks to individuals by indirect food chain pathways (i.e., risks from ingestion of contaminated crops, livestock, or fish). The indirect exposure model estimates the fate and transport of constituents in the soil and air through the environment and the food chain to produce human health risk estimates.

The model estimates exposure point concentrations in plant and animal tissue. Key inputs necessary to estimate exposure point concentrations in plant tissue include uptake rates into plants from soil (soil-plant uptake factor [Br]) and vapor (air-to-plant transfer factor [Bv]) and deposition of particles onto plant surfaces. The food chain transfer factors used to estimate exposure point concentrations in animal tissue included beef and dairy transfer factors to represent uptake of constituents in plants into the lipid fraction of beef and dairy products. For this analysis, the constituent-specific Monte Carlo inputs included a distribution of values for Br. All other values for food chain biotransfer factors were considered constituent-specific constant values.

The model also estimates the exposure point concentration in fish. The concentration of constituents in fish tissue is dependent on the concentration of constituents in the stream environment. The constituent concentration in fish tissue was estimated using constituent- specific constant values for the biotransfer factors. For metals, these factors are bioaccumulation factors (BAFs) representing transfer from the dissolved water column to fish tissue or bioconcentration factors (BCFs) representing transfer from the total water column (dissolved and suspended solids); however, for dioxins, bioaccumulation from sediment factors (BASFs) are used. The fish ingestion pathway and the ecological screening analysis are estimated using the same exposure point concentrations estimated for the stream environment.

5.2.2.4.1 *Estimation of Metals and Dioxin Concentrations in Plants Grown in Fertilizer-Amended Soil*. Plant bioaccumulation of metals and dioxins is assumed to be associated with different primary transfer processes. Metals are assumed to be incorporated into plant tissue primarily through root uptake of metals from the soil. Plants are also subject to aerial deposition of fertilizer material stirred up or dispersed into the air during tilling. For the human ingestion pathway, it is assumed that all but a small proportion of aerially deposited particulates are washed off before eating; farm animals are assumed to ingest whatever particulates were deposited on feed crops. Air deposition rates are estimated in the air dispersion model (see Section 5.2.2.1). The plant-soil uptake factors (Brs) for metals used in this assessment were developed specifically for this effort because existing Br values were not directly applicable to the specific conditions of metals applied with fertilizers to agricultural soil. The methodology used to collect Br data for this assessment is discussed below.

Dioxin congeners are assumed to be incorporated through root uptake and air-to-plant transfer. The methodology presented in *Estimating Exposure to Dioxin-Like Compound,* *Volumes I-III: Site-Specific Assessment Procedures* (U.S. EPA, 1994a) is followed for this analysis. A plant uptake factor (Br) is used to estimate the bioconcentration of each congener in aboveground crops, and a root concentration factor (Rcf) was used for root crops. Values for Br and Rcf are taken from the dioxin document (U.S. EPA, 1994a). The value for these parameters for each dioxin and furan congener is presented in Appendix K.

Rainsplash of soil onto the lower leaves of vegetation is not incorporated in the current analysis. Rainsplash is a mechanism of direct transfer of soil to the lower leaves of vegetation and could be included as an additional source of contamination for aboveground produce and forage (Dreicer and Whicker, 1984).

5.2.2.4.1.1 Soil-to-Plant Uptake Factors for Metals. Plant uptake factors (Brs) estimate the concentration of a contaminant in plant tissue as a function of the concentrations in the soil. In planning for this analysis, EPA evaluated Br values used in similar assessments, including the analysis conducted for EPA's Standards for the Use or Disposal of Sewage Sludge (40 *Code of Federal Regulations* [CFR] Part 503) and the fertilizer risk assessment conducted by the state of California (CDFA, 1998). Uptake factors derived for the Part 503 standards are specific to sewage sludge matrices and are inappropriate for estimating biouptake for fertilizer-amended soil. The data used in the California study are specific to fertilizers and, therefore, can be appropriately used here, but the data set is limited. Consequently, EPA developed a more comprehensive database on Br values for metals specifically for this analysis. The EPA database combines plant uptake data from several significant sources, including:

- California Department of Food and Agriculture's (CDFA's) *Risk-Based Concentrations for Arsenic, Cadmium, and Lead in Inorganic Commercial Fertilizers* (CDFA, 1998)
- Oak Ridge National Laboratory's (ORNL's) *Methods and Tools for Estimation of the Exposure of Terrestrial Wildlife to Contaminants* (Sample et al., 1997)
- ORNL's *Empirical Models for the Uptake of Inorganic Chemicals From Soil By Plants* (Bechtel Jacobs, 1998)
- Chaney and Ryan's *Risk Based Standards for Arsenic, Lead, and Cadmium in Urban Soils* (Chaney and Ryan, 1994).

For the data collection effort, all concentration data were screened based on their study type. Data from sewage sludge applications were not included, and data from greenhouse studies were noted as such. Uptake factors were developed from a combined data set including both greenhouse and field data and from a data set of field data only.

Data Entry Criteria

Sources used in the CDFA, Sample et al., and Chaney and Ryan reports were acquired for data extraction and entry into the fertilizer database. All retrieved literature was reviewed to determine if the data were appropriate for entry into the database. The data review and extraction methods described in the Bechtel Jacobs report were reviewed and found to be compatible; these data were entered into the database directly from tables in the report. Data from all four sources were entered only if they were from a primary source and presented corresponding soil and tissue concentrations. Additionally, only data presented numerically or in a format allowing reliable estimation of numeric values were entered. Regression data were not included. Data for elements reported in combination were not included. Only individual elements were included. For those data determined to be appropriate for entry, the following decisions were made:

- Only data from soil depths of 0 to 15 cm were included because the risk model assumes a tilling depth of that range.

- If present, the values adjusted for possible soil contamination from residue soil were entered.

- Total concentration was entered, as opposed to exchangeable or any other form of partial measurement.

- Amended soil concentrations were entered, and background concentrations were noted where available.

- Because of potential variability, plant weights were not included.

- Where available, it was noted whether the plant tissue was washed to account for possible soil contamination from residue soils.

To prevent inaccuracies in the database, a quality control (QC) check was performed on all entered data. The QC check was performed by an auditor other than the data enterer and consisted of checking 100 percent of the entered data against the original reference. Audit findings were documented on the hardcopy printout of the data. Upon completion of the QC check, the data entry personnel reviewed the comments, made the appropriate changes, and noted on the hardcopy printout that the changes had been made. Explanations of why any indicated changes were not made were also noted on the hardcopy printout.

The data included in the plant uptake database include metal concentrations in corresponding soil and plants, as well as soil and plant species descriptors. Table 5-6 lists the data elements included.

Table 5-6. Plant Uptake Data Elements

Data Elements	Description
Study ID	Identification of source reference
Constituent	Metal
Chemical form	Chemical form of metal measured
Valence state	Valence of measured constituent
Media	Soil or solution
Soil type	Soil classification
Soil pH	Reported range and mean values
Study type	Field or greenhouse study
Plant part	Reported plant part in which concentration was measured
Plant FFC	Farm food chain category
Plant species	Common name of study plant
Plant uptake category	Root, fruit, grain, herbaceous part, or forage
OC%	Soil organic content
Clay %	Soil clay content
Soil concentration	Measured constituent concentration in soil
Tissue concentration	Measured constituent concentration in plant tissue

Plant Categories

Because the plant uptake database combines three existing data sets, it comprises a particularly wide variety of plant species and plant parts for which concentration data are reported. Furthermore, the terminology used and the level of specificity varies among reports (e.g, aboveground parts, herbage, stems, shoots). In order to develop uptake factor distributions, the concentration data were divided into categories based on the plant part for which the metal concentration was reported. Distinct uptake factor distributions were then developed for each category and for each metal.

The basis for the category divisions was the plant part for which plant tissue concentrations were reported. EPA assumed that plant uptake and translocation of metals are distinct in roots versus aboveground parts and flowering or fruiting structures. This assumption is based on evidence in the primary data sources, several of the reports from which data were extracted, and general texts on plant uptake mechanisms and translocation (Farago, 1994; Fitter and Hay, 1983; Raven et al., 1982; Wilkins, 1990) that metal contaminants are differentially translocated to roots, aboveground leaves and stems, and flowering/fruiting parts. The following five plant part categories were used in this assessment:

- roots,
- grains,
- fruits (e.g., fruits, flowers, nuts, seeds),
- herbage (nonreproductive aerial parts consumed by humans), and
- forage (nonreproductive aerial parts consumed by animals but not humans).

The distinction between grains and other reproductive parts (fruits) reflects the fact that uptake in grains is frequently studied and reported separately and uptake by grain species is assumed by many investigators to be distinct. For the fertilizer risk assessment, grains are limited to plants in the *Poaceae* (grass) family. Although livestock feed can consist largely of grains, the grain category does not necessarily include all animal feed. For example, soy beans, common in livestock feed, are in the legume family and are not considered grains.

The distinction between human and nonhuman consumption (herbage versus forage) allows differentiation in the risk model between exposure through ingestion of plant matter and ingestion of animal products (e.g., beef and dairy products). Both of these categories include primarily leaf and stem parts and could arguably be combined. Moreover, the uptake factor distributions for these two categories are generally similar. The forage category includes a larger number of data pairs for each metal and, thus, the distributions are wider; for most metals, however, the herbage uptake factor distributions are contained within the forage uptake factor distributions. Further discussion of the relationship between these two categories is presented in Appendix G.

The fruit category, by definition, includes conventional fruits (e.g., apples) as well as some foods commonly thought of as vegetables, such as squash, beans, and peas. These are grouped together because metal uptake and translocation are assumed to be distinguished based on plant morphology (i.e., the physical structure or part). Many vegetables are the product of a fertilized flower and are, therefore, considered fruits. On the other hand, conventional vegetables not from the flowering/fruiting portion of a plant (e.g., lettuce and other leafy vegetables) are included in the herbage category, which is defined as aboveground, nonreproductive, edible parts.

Exclusion of Sewage Sludge Uptake Data

The uptake factors for this assessment have been developed excluding any data derived from studies based on the application of sewage sludge because the phytoavailability of metals is significantly lower in sewage sludge-amended soil. The specific metal adsorption capacity of sewage sludge results in increased metal adsorption in sludge-amended soil and, thus, a decreased availability of metals for plant uptake (Bechtel Jacobs, 1998; Chaney and Ryan, 1994; U.S. EPA, 1992). This is assumed to occur due to the presence of hydrous iron, manganese, and aluminum oxides within the biosolids matrix. Therefore, inclusion of data from studies sewage sludge studies would result in uptake factors that are not truly representative of uptake mechanisms in inorganic fertilizer-amended soil. For this assessment, no sewage sludge-derived data were used for any plant categories for any metal.

Greenhouse Versus Field Studies

Plant uptake rates also vary significantly between greenhouse or "pot" studies and field studies. Uptake rates for plants grown under greenhouse conditions as well as for plants grown in pots outdoors are higher than those for plants grown under field conditions. This difference is demonstrated when metals in the same form (e.g., sewage sludge or metal salts) are applied at the same rates to field versus pot or greenhouse plants. Plants grown in pots in greenhouses generally have the highest uptake rates. These higher uptake rates occur due to higher transpiration rates in relatively warm, humid greenhouse conditions. Moreover, test applications of metals are added to a limited soil volume in the pot and, thus, are more concentrated, increasing the diffusion of metals from soil particles to roots. When fertilizers containing NH_4-N are applied, rhizosphere acidification in the small volume of the pot can increase metal uptake (U.S. EPA, 1992). Because greenhouse study data tend to show higher uptake rates than field study data and, therefore, may not accurately represent agricultural settings, using only field data to develop plant uptake factors is generally recommended, if possible (Chaney and Ryan, 1994).

However, many of the uptake studies described in the literature are pot studies, and the available data are not evenly distributed across metals or across crop categories. Some metal-crop category combinations have little or no field data. Therefore, both field and pot study data were initially included in the uptake factor database. Each data point was tagged as field study-derived or pot study-derived, and two distinct sets of uptake factor distributions were developed: one using all data (field and pot) and one using only field study data. A sensitivity analysis was then performed to determine the effect of including pot study data.

The sensitivity analysis assessed the difference in the risk for each metal of concern using soil uptake values based on field data only versus soil uptake values based on field and pot data combined. For the sensitivity analysis, the 50th and 90th percentile uptake factor values for field only studies and field and pot studies combined were used as inputs to the indirect risk equations. All other factors in the analysis were held constant at central tendency values. The resulting risks to farmers for each pathway and all ingestion pathways were compared. The risk results for the farmer using the 50th percentile Br derived only from field studies for each metal were compared to the farmer’s risk results using the 50th percentile Br derived from field and pot studies. The same comparison was done using the 90th percentile Br values. Based on the results of the sensitivity analysis, as well as on numerous reports in the literature indicating that pot study data show significantly higher uptake rates, EPA concluded that uptake factors based only on field study data are most appropriate for use in the fertilizer risk assessment. Thus, the risk assessment results presented in Section 7.0 are based on plant uptake factors derived only from field study data where data were available. The model includes pot study data in cases where no other data were available.

Available field-derived data are adequate for developing uptake factor distributions for most of the compounds assessed in this analysis. Generally, less field data are available for fruits and grains than for other crop categories, particularly for mercury, cadmium, chromium, and copper. Field data are not available for nickel for three crop types: fruits, grains, and roots. Field data are also not available for vanadium for fruit, grain, herbage, and root crop types. Further discussion of the development of Br distributions is presented in Appendix G.

5.2.2.4.1.2 ***Biotransfer of Dioxins***. For dioxins, the methodology presented in *Estimating Exposure to Dioxin-Like Compound, Volumes I-III: Site-Specific Assessment Procedures* (U.S. EPA, 1994a) is followed for this analysis. Vegetation is classified as aboveground or belowground (belowground vegetation includes root vegetables such as carrots, potatoes, and radishes).

Soil to Plant Bioconcentration Factors

The Br parameter was used only for aboveground fruits and vegetables. The following equation from Travis and Arms (1988) was used by EPA (1993a, 1995a) to calculate the BCF in aboveground vegetables for organic chemicals when experimental data were not available in the literature:

$$\log(Br) = 1.588 - 0.578 \log(K_{ow}) \tag{5-34}$$

where

Br = plant-soil BCF [(µg/g plant tissue)/(µg/g soil)]
K_{ow} = octanol-water partition coefficient (L/kg).

A root concentration factor (Rcf), is used for root vegetables. The Rcf is a ratio of the concentration in roots to the concentration in soil pore water. A relationship between Rcf and K_{ow} was derived by Briggs et al. (1982) from experimental measurement of chemical uptake by barley roots, as follows:

$$\log(Rcf - 0.82) = 0.77\log(K_{ow}) - 1.52 \tag{5-35}$$

where

Rcf = root concentration factor [(µg/g plant tissue)/(µg/mL soil water)].

Air-to-Plant Biotransfer Factors

Another route of exposure for vegetation is direct deposition of particles and vapors to plant surfaces. The air-to-plant biotransfer factors for dioxins are constituent-specific values specifically developed for use for dioxin congeners (Lorber, 1995). These factors were developed through experiments conducted using azalea leaves and, for that reason, this algorithm may significantly overestimate the concentration of constituents in bulky aboveground produce.

Given the shape of bulky produce, transfer of contaminants to the center of the fruit or vegetable is unlikely to occur, so the inner portions of the dietary item will be largely unaffected. In addition, typical removal mechanisms, such as washing, peeling, and cooking, will further reduce contaminant residues. Therefore, applying these air-to-plant biotransfer factors directly will result in significant overestimation of contaminant concentrations. An adjustment factor (VG_{AG}) has been incorporated into the equations to address the overestimation for lipophilic compounds (K_{OW} >4). In this analysis, VG_{AG} was assigned a value of 0.01 for dioxins for all exposed fruits and vegetables intended for human consumption. (The forage crops used as cattle feed in the beef and dairy pathways were assigned a VG_{AG} value of 1.) The chemical-specific air-to-plant biotransfer factors for exposed fruits and vegetables are presented in Appendix K.

Interception Fraction

The interception fraction (Rp) is another factor that "accounts for the fact that not all of the airborne material depositing within a unit area will initially deposit on edible vegetation surfaces" (U.S. EPA, 1990). Interception fraction is calculated from crop yield. The interception fraction for exposed fruits was calculated directly using the following equation (Baes et al., 1984):

$$Rp = 1 - e^{-\Upsilon * Yp} \tag{5-36}$$

where

Rp = interception fraction
Υ = empirical constant
Yp = crop yield (kg DW/m^2).

The interception fraction for exposed vegetables is estimated as a consumption-weighted average for the three components of this category. The interception fractions for the categories of fruiting vegetables, leafy vegetables, and legumes are calculated using the same equation. Table 5-7 lists the specific vegetables included in the three groups. The unweighted crop yields were used with values for the empirical constant suggested by Baes et al. (1984) for each type of vegetable.

Table 5-7. Fruits and Vegetables Included in Yp and Rp Calculations

Fruits	Fruiting Vegetables	Legumes	Leafy Vegetables
Apple Apricot Berry Cherry Cranberry Grape Peach Pear Plum/Prune Strawberry	Asparagus Cucumber Eggplant Sweet Pepper Tomato	Snap Beans	Broccoli Brussels Sprouts Cabbage Cauliflower Celery Lettuce Spinach

<u>Crop Yields</u>

The crop yields for exposed fruit, exposed vegetables, and forage are derived using the following method. Crop yields were estimated from dry harvest yield and area harvested as follows (Shor et al., 1982):

$$Yp \approx Yh/Ah \qquad (5\text{-}37)$$

where

Yp = crop yield (kg DW/m^2)
Yh = dry harvest yield (kg DW)
Ah = area harvested (m^2).

Crop Yields for Exposed Vegetables and Fruits – Crop yields for exposed vegetables are estimated as a consumption-weighted average of values for fruiting vegetables, leafy vegetables, and legumes. The crop yield for exposed fruit does not need to be weighted because the fruit is considered a single category of produce. Table 5-7 lists the specific fruits and vegetables included in each of the groups. Table 5-8 summarizes the calculations. U.S. average harvest yield and area harvested values for 1993 for the fruits and vegetables listed in Table 5-7 were used (U.S. Department of Agriculture [USDA], 1994a, 1994b). Average harvest yield values are converted to dry weight using average conversion factors for fruits, fruiting vegetables, leafy vegetables, and legumes (Baes et al., 1984). Crop yields are then calculated for fruits, fruiting vegetables, leafy vegetables, and legumes using Equation 5-37. The exposed vegetable crop yields are then weighted by relative consumption of each group to determine the exposed vegetables weighted average crop yield of 3 kg DW/m^2. The exposed fruit crop yield was determined to be 0.25 kg DW/m^2.

The consumption rates for the fruiting vegetables, leafy vegetables, and legumes are derived from *Technical Support Document for Land Application of Sewage Sludge* (U.S. EPA, 1992c); they are presented as dry weight in the source document. The consumption rates used for weighting the three vegetable categories do not correspond exactly to the consumption rate of exposed vegetables used to calculate risk. The consumption rates used to calculate risk are derived from the *Exposure Factors Handbook* (EFH) (U.S. EPA, 1997a) and are considered to be the best currently available; however, similar relative intake fractions of each vegetable category are assumed to exist in both sets of data. Therefore, it is assumed that the data in Table 5-8 are applicable to this risk assessment even if the intake rates are not identical.

Crop Yield for Forage - Crop yield for forage is estimated as a weighted average of crop yields for pasture grass and hay. A crop yield value for pasture grass of 0.15 kg DW/m^2 was used (U.S. EPA, 1994a); this is a direct estimate because estimates of harvest yield and acres are not available for pasture grass. For hay, a dry harvest yield of 1.22E+11 kg DW was estimated from the U.S. average harvest yield for hay for 1993 of 1.35E+11 kg WW (USDA, 1994c) using a dry weight conversion factor of 0.9 (Fries, 1994). The U.S. average area harvested for hay for 1993 was 2.45E+11 m^2 (USDA, 1994c). Using these figures, a crop yield of 0.5 kg DW/m^2 was estimated using Equation 5-37. The crop yields are weighted based on the fraction of a year cattle could be pastured; the weights used are 0.75 for pasture grass and 0.25 for hay, based on 9 months per year in pasture and 3 months per year not in pasture (and fed hay). This results in a weighted crop yield for forage of 0.24 kg DW/m^2.

Table 5-8. Calculation of Crop Yield (Yp) for Fruits and Aboveground Vegetables

	Area Harvested (acres)	**Area Harvested (m^2)**	**Harvested Yield (kg WW)**	**Harvested Yield (kg DW)**	**Unweighted Crop Yield (kg DW/m^2)**	**Intake (g DW/d)**	**Weight Based on Intake (unitless)**	**Weighted Crop Yield (kg DW/m^2)**
Fruit	2E+06	8.10E+09	1.36E+10	2.05E+09	0.25	NA	NA	NA
Leafy vegetables	5.86E+05	2.37E+09	6.77E+09	5.82E+08	0.24	2.0	0.133	0.032
Fruiting vegetables	6.52E+05	2.64E+09	4.41E+11	2.78E+10	10.5	4.2	0.28	2.94
Legumes	2.84E+05	1.15E+09	7.73E+08	8.59E+07	0.075	8.8	0.587	0.044
Total								**3**

DW = Dry weight.
WW = Whole weight.
NA = Not applicable.

Note: WW to DW conversion factors: fruits, 0.15; leafy vegetables, 0.086; fruiting vegetables, 0.063; and legumes, 0.11.

Interception Fractions

Interception fractions for exposed vegetables are estimated as a consumption-weighted average of values for fruiting vegetables, leafy vegetables, and legumes. The interception fraction for exposed fruit does not need to be weighted because this group contains only one category of produce. Table 5-7 lists the specific fruits and vegetables included in each of the groups.

Interception Fractions for Exposed Vegetables and Exposed Fruit – Table 5-9 summarizes the calculations for interception fractions. Unweighted whole weight crop yields were used with values for the empirical constant suggested by Baes et al. (1984) for each type of fruit or vegetable. The unweighted dry weight crop yields are converted to whole weights. The interception fractions for fruiting vegetables, leafy vegetables, and legumes are then weighted by relative consumption of each group to determine the weighted average exposed vegetable interception fraction of 0.3. The exposed fruit interception fraction is 0.05.

The consumption rates for the fruiting vegetables, leafy vegetables, and legumes are derived from *Technical Support Document for Land Application of Sewage Sludge* (U.S. EPA, 1992c); they are presented as dry weights in the source document. The consumption rates used for weighting the three vegetable categories do not correspond exactly to the consumption rate of exposed vegetables used to calculate exposure. The consumption rates used to calculate exposure were considered to be the best currently available; however, similar relative intake fractions of each vegetable category are assumed to exist in both sets of consumption rate data.

Table 5-9. Calculation of Interception Fraction (Rp) for Exposed Fruits and Vegetables

	Unweighted Crop Yield (kg WW/m^2)		**Unweighted Interception Fraction (unitless)**	**Intake (g DW / d)**	**Weight**	**Weighted Interception Fraction (unitless)**
Fruit	1.68	0.0324	0.053	NA	NA	NA
Leafy vegetables	2.85	0.0846	0.21	2.0	0.133	0.028
Fruiting vegetables	167	0.0324	1.0	4.2	0.28	0.15
Legumes	0.67	0.0324	0.022	8.8	0.587	0.013
Total vegetable						**0.3**

DW = Dry weight.
WW = Whole weight.
Unweighted crop yield was estimated based on data presented in Table 4-10 for area harvested (m^2) and harvested yield (kg WW).
NA = Not applicable.

Interception Fraction for Forage – The interception fraction for forage is estimated from the weighted average crop yield for pasture grass and hay. Chamberlain (1970) gives a range for the empirical constant of 2.3 to 3.33. The midpoint of the range, 2.88, was used, as suggested by Baes et al. (1984). Both the hay and the pasture grass dry weight crop yields are converted to a whole weight basis prior to use in the above equation. The resulting interception fraction is 0.5 (Chamberlain, 1970).

5.2.2.4.2 ***Estimation of Metals and Dioxins in Beef and Dairy Fed Vegetation Grown on Fertilizer-Amended Fields***. Risks in the farmer scenario may occur through the ingestion of plants grown on amended soil and products from animals raised on fields amended with fertilizers. In this analysis, the only animal products considered are beef and milk. Beef and dairy items have high lipid contents and, therefore, may be expected to have higher concentrations of lipophilic constituents than other animal products such as poultry meat, eggs, pork, or lamb. The biotransfer factors for beef and dairy items are also more thoroughly documented than those for pork, poultry, lamb, and so on. The beef and milk biotransfer factors for all constituents are presented in Appendix K.

The constituent concentrations their beef and dairy products are estimated based on dietary intake assumptions for cattle. Their diet is assumed to consist of forage (i.e., pasture grass and hay), silage, and grain grown on fertilizer-amended soil. In addition, cattle are assumed to ingest the amended soil.

The intake of grain, silage, forage, and soil is assumed to vary between dairy and beef cattle. The diet of beef cattle is assumed to be mainly pasture grasses, hay, and silage. Soil consumption is assumed to be high because of the time spent in pasturage. The total consumption rates for typical beef cattle are lower because they are slaughtered younger and lighter. Unlike beef cattle, dairy cows are assumed to be confined, so grazing is infrequent, their diet is supplemented with increased grain, and their soil intake is more limited.

The total consumption of constituents of concern in feed is calculated as a sum of the constituent concentrations resulting from the following mechanisms:

- Root uptake – Constituents available from the soil and their transfer to the aboveground portion of the plant,
- Deposition of particles – Dry deposition of particle-bound constituents on plants, and
- Vapor transfer – Uptake of vapor-phase constituents by plants through their foliage.

The vegetation was classified as protected or unprotected. Grain and silage are considered to be protected because the outer covering acts as a barrier to the deposition of particles and vapor transfer and only root uptake is assumed to occur. Forage is assumed to be unprotected, and all routes of contamination are assumed to be present. The cattle dietary factors affecting concentrations of constituents of concern are presented in Table 5-10.

Table 5-10. Cattle Consumption Factors Affecting Concentrations of Constituents in Beef and Dairy Products

Parameter	Beef Cattle	Dairy Cows	Reference
Length of exposure to deposition			
Forage	0.12 yr	0.12 yr	
Silage	0.16 yr	0.16 yr	U.S. EPA, 1990
Consumption by cattle			National Academy of Sciences (NAS), 1987; Boone et al., 1981; Rice, 1994
Forage	8.8 kg/d (DW)	13.2 kg/d (DW)	
Grain	0.47 kg/d (DW)	3.0 kg/d (DW)	
Silage	2.5 kg/d (DW)	4.1 kg/d (DW)	
Soil	0.5 kg/d	0.4 kg/d	Soil only: Fries, 1994

yr = Year.
DW = Dry weight.

5.2.2.5 IEUBK Model for Lead

Human health risk assessment for lead is unique. Instead of developing a health benchmark in the traditional manner, all identified sources of lead exposure (including the background) are used to predict blood lead (PbB) levels in exposed individuals. The predicted PbB levels are compared to a target PbB. PbB levels have long been used as an index of body lead burdens and as an indicator of potential health effects.

The Integrated Exposure Uptake Biokinetic (IEUBK) model (U.S. EPA, 1994d) was developed to predict PbB levels for an individual child or a population of children. The model was specifically designed to evaluate lead exposure in young children (birth to 7 years of age) because this age group is known to be highly sensitive to lead exposure. The pharmacokinetic relationships in the IEUBK model, in fact, are only valid for those 7 years old or younger.

The IEUBK model integrates lead exposures from diet, soil, dust, drinking water, and air and also considers elimination of lead from the body. The model uses standard age-weighted exposure parameters, and its simulations represent chronic exposure and do not incorporate the variability in consumption patterns and media concentrations on a seasonal or daily basis. The IEUBK model simulates uptake, distribution within the body, and elimination of lead from the body. The uptake portion of the model takes into consideration two mechanisms of absorption of lead: saturable and nonsaturable. Elimination of lead is modeled through several routes: urine, gastrointestinal excretion, and sloughing of epidermal tissue, including hair and nails.

Exposure pathways evaluated for lead uptake for this analysis include, direct ingestion of fertilizer-amended soil, and ingestion of lead- contaminated produce.

5.2.2.5.1 ***Application of the Model***. The default assumptions in the IEUBK model for ingestion of soil and dust are used in this analysis without change. The total daily dietary intake of lead (dietary routes include vegetable, fruit, root, beef, and dairy) in milligrams was calculated and entered into the IEUBK model in order to estimate a probability of reaching a blood lead level of 10 µg/DL. This allows use of the same dietary intake assumptions used throughout the analysis for estimating the hazard associated with lead.

The IEUBK model has another method for assessment the risks associated with the ingestion of homegrown vegetables and fruits by young children. This method requires the user to enter the concentration of lead present in the fruit and vegetable products and uses default ingestion rates to estimate the resulting blood lead levels. This method has been used in this case only for comparison with the values obtained from the dietary intake method. Because of the intricate nature of this methodology, only the maximum 90th percentile lead concentrations have been evaluated by this method.

5.2.2.5.2 *Exposure Factors*.

Soil Ingestion

The default soil ingestion parameters in the IEUBK model are assumed for this risk assessment. This parameter is considered to be one of the most important in this model, and the default assumptions are considered the most appropriate for this application.

Table 5-11. Exposure Parameters for Incidental Ingestion of Fertilizer Product

Exposure Parameter	Resident Farm Child	Reference
Body weight	Children aged 1 to 5 yr	EFH
Exposure duration	Children aged 6 months to 7 yr	IEUBK model
Soil ingestion rate	Default soil intake	IEUBK model

6.0 Exposure and Toxicity Assessments

The exposure factor data used in the risk analysis are derived from the *Exposure Factors Handbook* (EFH) (U.S. Environmental Protection Agency [EPA], 1997a, 1997b, 1997c). The health benchmark values for metals are based on the values presented in the online database Integrated Risk Information System (IRIS) or the Health Effects Assessment Summary Tables (HEAST). The values for the dioxin congeners are based on the toxicity equivalent factors (TEF) methodology presented in *Interim Procedures for Estimating Risks Associated with Exposures to Mixtures of Chlorinated Dibenzo-*p*-dioxins and -dibenzofurans (CDDs and CDFs) and 1989 Update* (U.S. EPA, 1989).

6.1 Exposure Factors

The exposure assumptions for each receptor scenario are presented in Table 6-1. In this risk assessment, it is assumed that the farmer is also a recreational fisher and, thus, consumes home-caught fish from a stream adjacent to the agricultural field where fertilizer products are applied.

Table 6-1. Ingestion Exposures for Receptor Scenarios

	Farmer	Child of Farmer
Dietary		
Exposed fruits	✓	✓
Exposed vegetables	✓	✓
Root vegetables	✓	✓
Beef	✓	✓
Dairy products	✓	✓
Fish	✓	✓
Nondietary		
Fertilizer	✓	
Soil	✓	✓

6.1.1 Consumption Factors Required for Receptor Scenarios

The consumption rates used in this risk analysis are taken from the 1997 EFH. The intake rates presented in the EFH are based, where possible, on Nationwide Food Consumption Survey (NFCS) data. According to the 1997 EFH, the U.S. Department of Agriculture (USDA) conducts the NFCS every 10 years to analyze the food consumption behavior and dietary status of Americans. The 1987-88 survey was used as a basis for the 1996 EFH. The survey used a statistical sampling technique designed to ensure that all seasons, geographic regions of the 48 conterminous states, and socioeconomic and demographic groups were represented. Data on the socioeconomic and demographic characteristics of households and the types, amount, value, and sources of food consumed by the households were collected over a 7-day period. Data on food intakes of individuals within each household were collected over a 3-day period. Although these data are the best available, they are derived from short-term studies that may not reflect long-term behaviors. The data collected represent the total amount of food products brought into the household during the week and divided by the number of household members. The data do not include losses due to preparation and cooking. The sample size for this survey was approximately 4,300 households (more than 10,000 individuals). These data were used to generate homegrown intake rates because, as the most recent data, they are believed to reflect current dietary patterns in the United States.

The percentiles of average daily intake derived for short time intervals will not reflect long-term patterns. The 1997 EFH developed an approach to account for seasonal variability in consumption by using seasonally adjusted distributions to approximate regional long-term distributions and then combining these regional adjusted distributions (in proportion to the weights for each region) to obtain a U.S.-adjusted distribution to approximate the U.S. long-term distribution.

6.1.1.1 <u>Incidental Ingestion of Fertilizer Products</u>. Farm adult residents who are assumed to have the highest exposure potential from incidental ingestion of fertilizer products, are evaluated for this pathway. Receptors most at risk for adult incidental ingestion of fertilizer products are adult farm workers who come into contact with fertilizer products during loading and application operations and resident farm adults who are exposed during application operations.

No distribution of specific values for incidental ingestion of fertilizer products is presented in EPA’s EFH. The California Department of Food and Agriculture (CDFA) conducted a tiered human health risk assessment to establish risk-based concentrations of arsenic, cadmium, and lead in manufactured, inorganic fertilizers distributed commercially in the state of California. Incidental ingestion of fertilizer products by adult farmers was considered as part of California’s risk analysis. EPA used the exposure assumptions provided in the California study to estimate the risk from incidental ingestion of fertilizer products for adult farm residents. The resident farm child was not assessed for direct ingestion exposure of fertilizer products in the California study. EPA’s fertilizer assessment also does not consider incidental ingestion of fertilizer products by children. Incidental ingestion is assumed to occur only during application of fertilizer products and only the applicators (adult farmers and farm workers) are assumed to be exposed in this manner. Exposure assumptions for incidental ingestion are presented in Table 6-2.

Table 6-2. Exposure Parameters for Incidental Ingestion of Fertilizer Product

Exposure Parameter	Farm Resident/ Farm Worker Adult	Reference
Body weight distribution Population estimated mean Population estimated standard deviation	Lognormal 71.2 kg 13.3 kg	EFH Tables 7-2, 7-3, 7-4, 7-5, 7-6, and 7-7
Exposure frequency	350 d/yr	Assumption
Exposure frequency for fertilizer application	16 d/yr Macronutrient 8 d/yr Micronutrient	California Risk Assessment (A-4) (TFI, 1999)
Exposure duration distribution Population-estimated mean Population-estimated standard deviation	Gamma 17.3 yr 18.7 yr	Adult EFH Tables 15-163 and 15-164
Fertilizer ingestion rate (assumed to be soil ingestion rate for the days of application)	50 mg/d	EFH Table 4-23

A key assumption taken from the California assessment is the fertilizer application period. For the California study, primary nutrient fertilizers were assumed to be applied 16 d/yr, and the same assumption has been made in this risk assessment. This duration was estimated based on the assumption that an individual can apply fertilizer to 20 acres per day and the fact that the average size farm in California is approximately 320 acres; thus, one person would need 16 days to apply fertilizer to an entire farm. This is not an applicable formula for the 90th percentile farm (750 acres). However, assuming that that more than one person would be required to complete the task in a timely manner, the 16 d/yr duration used by California is considered to be a valid assumption for this assessment. Therefore, the 16 d/yr exposure duration reported in the California document is used in this risk assessment. Generally, micronutrient fertilizers are applied less frequently than macronutrient fertilizers (The Fertilizer Institute [TFI], 1999). Micronutrient fertilizer application is assumed to occur at half the rate of macronutrient fertilizer application, or 8 d/yr for this assessment. The assumption micronutrient fertilizer application occur at approximately half the rate of macronutrient fertilizer application is consistent with assumptions made by TFI in a recently published assessment of fertilizer applicators (TFI, 1999).

Exposure parameters such as ingestion rates, exposure frequencies, and human body weights were used to calculate daily doses (or intake levels) for individual receptors (Table 6-2). The average daily dose was averaged over the exposure duration and represented the estimated chronic daily intake of a noncarcinogenic substance. The lifetime average daily dose was averaged over an individual's lifetime and represented the estimated chronic daily intake of a carcinogenic substance.

6.1.1.2 Ingestion of Soil. No distribution of specific values is presented in the draft 1997 EFH for soil ingestion for adults or children. Limited studies are available for estimating soil ingestion in adults. The 1997 EFH presents two studies (Calabrese et al., 1990; Hawley, 1985). These studies showed an average soil intake rate ranging from 0.5 to 110 mg/d. This range includes the recommended soil intake rate of 50 mg/d used by many EPA programs. The EFH suggests that 480 mg/d for adults engaged in outdoor activity may be used in screening for noncarcinogens. This distribution may or may not overestimate the frequency of high-end adult soil ingestion rates. With a limited data set (6 data points), an alternative to this distribution is to consider these values as a range of potential ingestion rates of equal probability.

Child soil ingestion rates have been studied more frequently and in greater detail than adult ingestion rates. Six large studies have been examined in detail for the EFH. It is assumed that all children (aged 1 to 6 years) ingest some soil through hand-to-mouth behavior. This normal pattern of ingestion is captured in the distribution of the range of means for child soil ingestion rates (39 to 245.5 mg/d; the average recommended value is 165 mg/d) presented in the EFH. This range of means is consistent with the 200-mg/d value that EPA programs have used as a conservative mean estimate.

The EFH indicates, however, that there is also an upper percentile range of child soil ingestion rates of 106 to 1,432 mg/d, with an upper percentile mean of 545 mg/d. The 1,432-mg/d value is presented as an upper percentile estimate in Calabrese et al. (1989), which includes children with pica behavior (the intentional ingestion of soil). Pica behavior presents additional concern when establishing a distribution of child soil ingestion rates. The EFH presents five key studies on soil ingestion in children. All these studies were short-term, and the prevalence of pica behavior unknown. It is, therefore, suggested that the range of child soil ingestion may be underestimated if the pica child is excluded from the distribution. The EFH presents data that indicate that an ingestion rate of 10 to 14 g/d may not be unreasonable for screening for noncarcinogens. The EFH notes that pica behavior might have been observed in additional children if studies were conducted for longer periods of time.

For this analysis, the lognormal model is used for soil consumption for all age groups. Parameter estimates, obtained by assuming the coefficient of variation (CV) equals 0.5, 1, and 1.5, are listed in Table 6-3 and Figure 6-1. Population standard deviations based on a CV of 1.5 are used for this analysis. Children aged 1 to 5 years are evaluated for this assessment.

6.1.1.3 Ingestion of Exposed Fruits and Vegetables and Root Vegetables. The intake rates presented in the EFH are presented in grams of fresh weight per day per kilogram of body weight. For all organic compounds and most metals, these intake rates remain in fresh (wet) weight equivalents for all dietary categories; however, for some metals, a dry weight consumption rate was required for the analysis for root vegetables and beef and dairy products.

Table 6-3. Ingestion of Soil

Group	Data Mean (mg/d)	Distribution	Population-Estimated Mean (mg/d)	Population-Estimated Standard Deviation (CV=0.5)	Population-Estimated Standard Deviation (CV=1)	Population-Estimated Standard Deviation (CV=1.5)
Age 1 to 5	100	Lognormal	100	50	100	150
Adult	50	Lognormal	50	25	50	75

The dry weight conversion factors are used to adjust the wet weight intakes for fruits, vegetables, root vegetables, and beef and dairy products presented in the EFH to dry weight for use with the bioconcentration or biotransfer factors required for this analysis. The dry weight consumption rate is needed for all compounds for fruits and exposed vegetables. The dry weights for root vegetables are used for all metals.

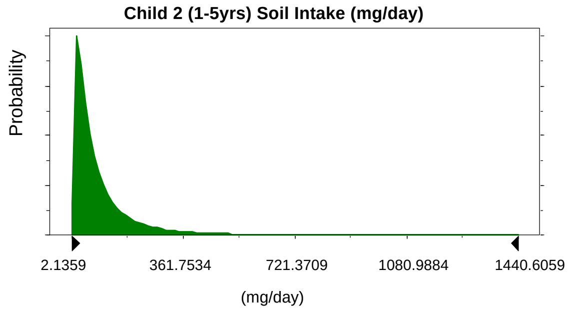

Figure 6-1. Soil intake (mg/d).

The following equation is used to convert the wet weight food consumption rate to a dry weight basis:

$$C_{DW} = C_{WW} * (1 - F_{MOISTURE}) \qquad (6\text{-}1)$$

where

C_{DW} = consumption in dry weight
C_{WW} = consumption in wet weight
$F_{MOISTURE}$ = fraction moisture.

The dry weight conversions for these dietary categories are presented in Table 6-4.

Table 6-4. Moisture Content of Food Items Used for Dry Weight Conversions

Food Category	Fraction Moisture Content
Fruits	0.851
Exposed vegetables	0.91.2
Root vegetables	0.8576
Beef	0.716
Dairy products	0.76

A fraction of the total intake is assumed to be home-produced. In this analysis, the agricultural field is assumed to be the contaminated area and, thus, the fractions that represent home-grown produce also represent the fraction of the dietary intake that is contaminated. These fractions are mean values used as a single value in the absence of additional data. This fraction assumed home-produced is presented in Table 12-71 of the EFH. Data from this table are presented in Table 6-5.

Table 6-5. Fraction of Dietary Item Home-Produced

Dietary Item	Fraction Home-Produced Consumed by Households that Farm
Exposed vegetables	0.420
Exposed fruit	0.328
Root vegetables	0.173
Beef	0.319
Dairy products	0.254

Exposed Fruit

Data on consumption of homegrown exposed fruit were obtained from Table 13-61 of the EFH (U.S. EPA, 1997b). Data (in g WW/kg/d) are presented by age groups and for farmers and home gardeners (adults). For children aged 1 to 5 years, data are only available for those 3 to 5 years old (not available for 1- to 2-year-olds); therefore, these data are used for the entire 1- to 5-year-old age group. Percentile data are used to fit parametric models (gamma, lognormal, Weibull) using maximum likelihood estimation. Goodness-of-fit measures are used to select the most appropriate model. The fraction of home-produced exposed fruit intake is 0.116 for households that garden and 0.328 for households that farm (EFH Table 13-71; U.S. EPA, 1997b). The distributions used for ingestion of exposed fruit are presented in Table 6-6 and Figure 6-2.

Table 6-6. Ingestion of Home-Produced Exposed Fruit (Table 13-61 of EFH)

Group	*N*	Data Mean	Data Standard Deviation	P50	P90	P95	P99	Distribution	Population-Estimated Mean	Population-Estimated Standard Deviation
Age 1 to 5	49	2.6	3.947	1.82	5.41	6.07		Gamma	2.25	1.89
Farmer	112	2.32	2.646	1.3	5	6.12	15.7	Lognormal	2.36	3.33

*In g WW/kg/d.
Data mean – Arithmetic average of data points.
Data standard deviation – Standard deviation of the distribution of data points.
Population-estimated mean – The mean value estimated from use of the assigned distribution.
Population-estimated standard deviation – The standard deviation value estimated from use of the assigned distribution.

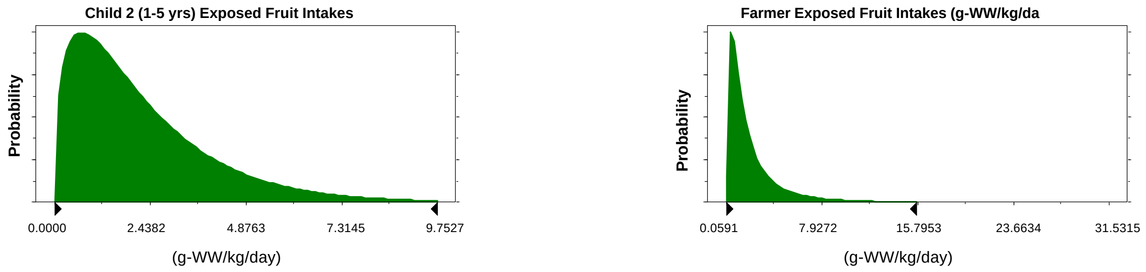

Figure 6-2. Child and farmer intake rates for home-produced exposed fruits.

Exposed Vegetables

Data on consumption of homegrown exposed vegetables were obtained from EFH Table 13-63 (U.S. EPA, 1997b). Data (in g WW/kg/d) are presented for 1- to 2-year-olds, 3- to 5-year-olds, 6- to 11-year-olds, 12- to 19-year-olds, 20- to 39-year-olds, 40- to 69-year-olds, farmers, and home gardeners. Weighted averages of percentiles, means, and standard deviations are calculated for the age group for children 1 to 5 years old (combined 1- to 2-year-olds and 3- to 5-year-olds). Percentile data are used to fit parametric models (gamma, lognormal, Weibull) using maximum likelihood estimation. Goodness-of-fit measures are used to select the most appropriate model. The fraction of home-produced exposed vegetable intake is 0.42 for households that farm (EFH Table 13-71; U.S. EPA, 1997b), as shown in Table 6-7 and Figure 6-3.

Table 6-7. Ingestion of Home-Produced Exposed Vegetables (Table 13-63 of EFH)

Group	*N*	Data Mean	Data Standard Deviation	P50	P90	P95	P99	Distribution	Population-Estimated Mean	Population-Estimated Standard Deviation
Age 1 to 5	105	2.453	2.675	1.459	6.431	8.587		Gamma	2.55	2.58
Farmer	207	2.17	2.316	1.38	6.01	6.83	10.3	Lognormal	2.38	3.5

*In g WW/kg/d.
Data mean – Arithmetic average of data points.
Data standard deviation – Standard deviation of the distribution of data points.

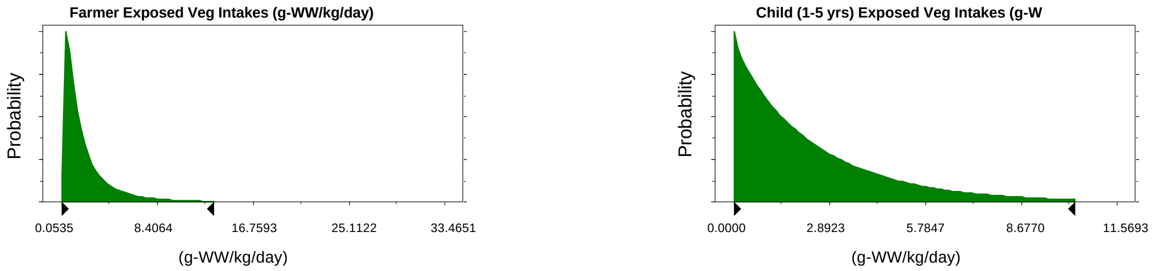

Figure 6-3. Farmer and child intake rates for home-produced exposed vegetables.

Population-estimated mean – The mean value estimated from use of the assigned distribution.
Population-estimated standard deviation – The standard deviation value estimated from use of the assigned distribution.

Root Vegetables

Homegrown root vegetable consumption data were obtained from EFH Table 13-65 (U.S. EPA, 1997b). Data (in g WW/kg/d) are presented for 1- to 2-year-olds, 3- to 5-year-olds, 6- to 11-year-olds, 12- to 19-year-olds, 20- to 39-year-olds, 40- to 69-year-olds, farmers, and home gardeners. Weighted averages of percentiles, means, and standard deviations are calculated for the age group for children 1 to 5 years old. Percentile data are used to fit parametric models. The fraction of home-produced root vegetable intake is 0.173 for households that that farm (EFH Table 13-71; U.S. EPA, 1997b), as shown in Table 6-8 and Figure 6-4.

Table 6-8. Ingestion of Home-Produced Root Vegetables (Table 13-65 of EFH)

Group	*N*	Data Mean	Data Standard Deviation	P50	P90	P95	P99	Distribution	Population-Estimated Mean	Population-Estimated Standard Deviation
Age 1 to 5	45	1.886	2.371	0.686	5.722	7.502		Lognormal	2.31	6.05
Farmer	136	1.39	1.469	0.883	3.11	4.58	7.47	Lognormal	1.45	2.06

*In g WW/kg/d.
Data mean – Arithmetic average of data points.
Data standard deviation – Standard deviation of the distribution of data points.

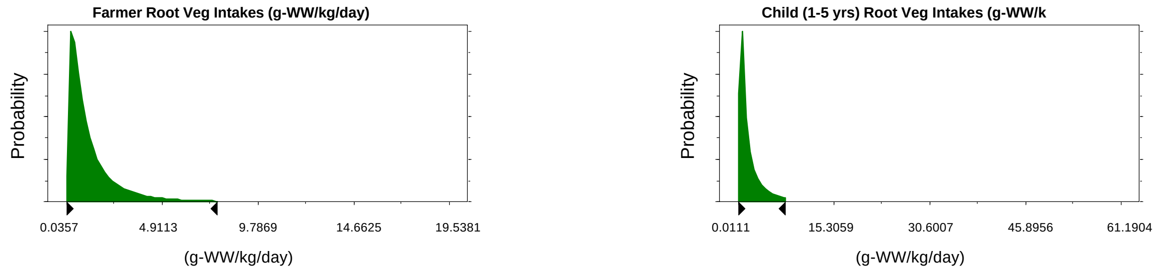

Figure 6-4. Farmer and child intake rates for home-produced root vegetables.

Population-estimated mean – The mean value estimated from use of the assigned distribution.
Population-estimated standard deviation – The standard deviation value estimated from use of the assigned distribution.

6.1.1.4 Ingestion of Beef and Dairy Products.

Beef

Home-produced beef consumption data were obtained from EFH Table 13-36 (U.S. EPA, 1997b). Data (in g WW/kg/d) are presented for 6- to 11-year-olds, 12- to 19-year-olds, 20- to 39-year-olds, 40- to 69-year-olds, and farmers. Percentile data were used to fit parametric models (gamma, lognormal, Weibull) using maximum likelihood estimation. Goodness-of-fit measures are used to select the most appropriate model. The fraction of home-produced beef intake is 0.485 for households that farm (EFH Table 13-71; U.S. EPA, 1997b).

Data are not available for 1- to 2-year-olds and 3- to 5-year-olds. For beef consumption for 1- to 5-year-olds, the lognormal model is used because, among the other age groups, it is the best fitted model in all but one case. The population-estimated mean and standard deviation for 6- to 11-year-olds are used for the analysis (normalized for body weight) and are supported by data in EFH Table 11-3 (per-capita intake for beef, including store-bought products), which indicate that 1- to 2-year-olds, 3- to 5-year-olds, and 6- to 11-year-olds have the highest consumption rate of beef on a g/kg/d basis. Ingestion rates for home-produced beef are presented in Table 6-9 and Figure 6-5.

Table 6-9. Ingestion of Home-Produced Beef (Table 13-36 of EFH)

Group	*N*	Data Mean	Data Standard Deviation	P50	P90	P95	P99	Distribution	Population-Estimated Mean	Population-Estimated Standard Deviation
Age 1 to 5		ND	ND					Lognormal	3.88	4.71
Farmer	182	2.63	2.644	1.64	5.39	7.51	11.3	Lognormal	2.5	2.69

*In g WW/kg/d.

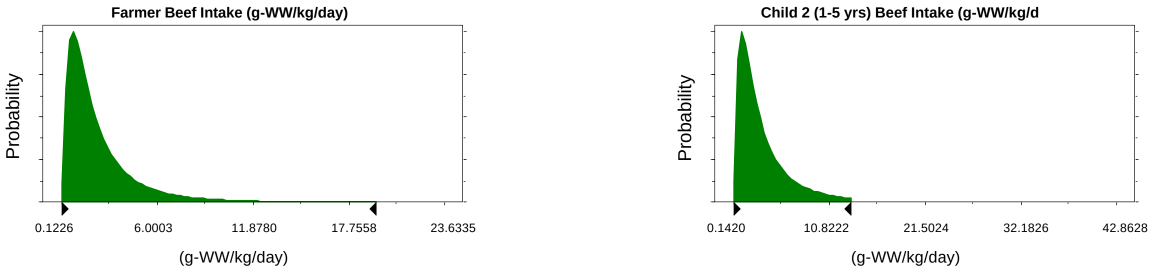

Figure 6-5. Farmer and child intake rates for home-produced beef.

Data mean – Arithmetic average of data points.
Data standard deviation – Standard deviation of the distribution of data points.
Population-estimated mean – The mean value estimated from use of the assigned distribution.
Population-estimated standard deviation – The standard deviation value estimated from use of the assigned distribution.

Dairy Products

Data on consumption of dairy products are obtained from EFH Tables 13-28 and 11-2 (U.S. EPA, 1997b). Data on consumption of home-produced dairy products (in g WW/kg/d) are presented for 20- to 39-year-olds and farmers (Table 13-28). Per-capita intake data for dairy products (including store-bought products) are available for those younger than 1 year, 1- to 2-year-olds, 3- to 5-year-olds, 6- to 11-year-olds, and 12- to 19-year-olds (Table 11-2). Weighted averages of percentiles, means, and standard deviations are calculated for the child2 age group (combined 1- to 2-year-olds and 3- to 5-year-olds). Percentile data are used to fit parametric models (gamma, lognormal, Weibull) using maximum likelihood estimation. Goodness-of-fit measures were used to select the most appropriate model. The fraction of home-produced dairy product intake is 0.254 for households that farm (EFH Table 13-71; U.S. EPA, 1997b). Ingestion rates for home-produced milk are presented in Table 6-10.

Table 6-10. Ingestion of Home-Produced Dairy Products (Milk) (Table 13-28 of EFH)

Group	*N*	Data Mean	Data Standard Deviation	P50	P90	P95	Distribution	Pop Estimated Mean	Population-Estimated Standard Deviation
Age 1 to 5	2	23.71	35.86	21.5	42.63	49.62	Weibull	23.6	14.3
Farmer	63	17.1	15.8	12.1	34.9	44	Weibull	16.3	13.1

*In g WW/kg/d.
Data mean – Arithmetic average of data points.
Data standard deviation – Standard deviation of the distribution of data points.
Population-estimated mean – The mean value estimated from use of the assigned distribution.
Population-estimated standard deviation – standard deviation value estimated from use of the assigned distribution.

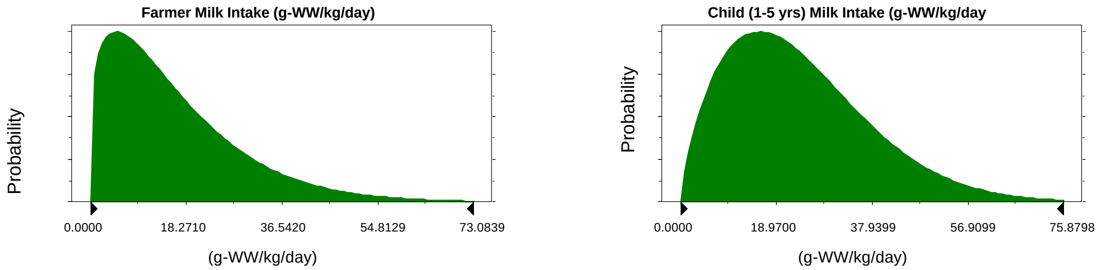

Figure 6-6. Farmer and child intake rates for home-produced milk.

Breast milk

Ingestion rates for breast milk are presented in Table 6-11 and Figure 6-6. The data mean and upper percentile for breast milk consumption in 1- to 12-month-olds are 688 and 980 mL/d, respectively (EFH Table 14-16; U.S. EPA, 1997b). The gamma model is used for breast milk consumption (1- to 12-month-olds) because it is the best fitted model for cow's milk data for this age group. The population-estimated mean for breast milk consumption is 688 mL/d, the population-estimated standard deviation for CV=1.5 is 1,032 mL/d.

Table 6-11. Ingestion of Breast Milk (Table 14-16 of EFH)

Group	Data Mean (mL/d)	Data Standard Deviation	Upper Percentile	Distribution	Population-Estimated Mean (mL/d)	Population-Est Std Deviation (mL/d)
Age <1	688	ND	980	Gamma	688	1,032

6.1.1.5 Fish Intake. Most fish ingestion is represented by the distribution of ingestion rates presented in the 1997 EFH for households that fish (recreational fishers). These ingestion rates are not protective of the highly selective population of subsistence fishers; however, for a nationwide risk assessment like this one, the distribution for recreational fishers in the EFH is considered most appropriate.

Fish consumption data are obtained from EFH Table 10-64 (U.S. EPA, 1997b). Data (in g/d) are for adult freshwater anglers in Maine. Age-specific data for children are not available; children are assumed to consume the same amount of fish as adults. Percentile data were used to fit parametric models (gamma, lognormal, Weibull) and goodness-of-fit measures were used to select the most appropriate model. The fraction of home-caught fish is 0.325 for households that fish (EFH Table 13-71; U.S. EPA, 1997b). Ingestion rates for home-caught fish are presented in Table 6-12 and Figure 6-7.

Table 6-12. Ingestion of Home-Caught Fish (Table 10-64 of EFH)

Group	*N*	Data Mean	Data Standard Deviation	P50	P90	P95	Distribution	Population-Estimated Mean	Population-Estimated Standard Deviation
Age 1 to 5	ND	ND	ND	ND	ND	ND	Lognormal	6.48	19.9
Age 20+	ND	ND	ND	ND	ND	ND	Lognormal	6.48	19.9

*In g/d.
Population-estimated mean – The mean value estimated from use of the assigned distribution.
Population-estimated standard deviation – The standard deviation value estimated from use of the assigned distribution.

6.1.2 Exposure Durations

Data for exposure duration for adults are obtained from the distributions presented for population mobility (EFH Chapter 14.3). There are data for numerous categories of residents. The population mobility distribution for farmers was used for the farmer scenario. The distributions used for the exposure duration for the farmer are presented in Table 6-13 and Figure 6-8. The exposure duration for children is assumed to be between 1 and 5 years. A uniform distribution with a minimum of one and a maximum of 5 was used for this analysis. No aging of children is done, as the highest intake rates per body weight are obtained for this age group.

For residence duration (in years) for farmers and rural residents (Israeli and Nelson, 1992, as cited in U.S. EPA, 1997b, EFH Tables 15-163 and 15-164), the gamma model is used because it is the best fitted model in five age groups and the second best fitted model in two cases (based on data by Johnson and Capel, 1992, as cited in U.S. EPA, 1997b, EFH Tables 15-167 and 15-168). A population-estimated mean and a population-estimated standard deviation of 17.31 and 18.69 years, respectively for farmers is used in the analysis.

Table 6-13. Exposure Duration (Residence Time)

Group	*N*	Data Mean	Data Standard Deviation	P50	P90	P95	P99	Distribution	Population-Estimated Mean	Population-Estimated Standard Deviation
Farmer	ND	17.31	18.69	ND	ND	ND	ND	Gamma	17.31	18.69

*In g WW/kg/d.
Data mean – Arithmetic average of data points.
Data standard deviation – Standard deviation of the distribution of data points.
Population-estimated mean – The mean value estimated from use of the assigned distribution.
Population-estimated standard deviation – The standard deviation value estimated from use of the assigned distribution.

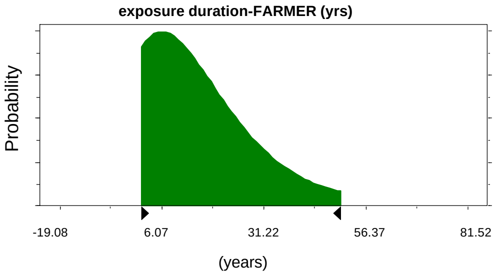

Figure 6-8. Farmer exposure duration assumption.

6.1.3 Body Weight

Body weight data are obtained from EFH Tables 7-2, 7-3, 7-4, 7-5, 7-6, and 7-7 (U.S. EPA, 1997a). Data (in kg) are presented by age and gender. Weighted averages of percentiles, means, and standard deviations are calculated for children younger than 1 year, 1- to 5-year-olds, 6- to 11-year-olds, 12- to 19-year-olds, and adult age groups. Male and female data are weighted and combined for each age group. Percentile data are used as the basis of fitting distributions. These data are analyzed to fit parametric models (gamma, lognormal, Weibull) using maximum likelihood estimation. Goodness-of-fit measures are used to select the most appropriate model. Body weight data are presented in Table 6-14 and Figure 6-9.

Table 6-14. Body Weights

Group	*N*	Data Mean	Data Standard Deviation	P50	P75	P85	P90	P95	Distribution	Population-Estimated Mean	Population-Estimated Standard Deviation
Age 1 to 5	3,762	15.52	3.719	15.26	16.67	17.58	18.32	19.45	Lognormal	15.5	2.05
Age 20+	12,504	71.41	15.45	69.26	78.49	84.92	89.75	97.64	Lognormal	71.2	13.3

*In g WW/kg/d.
Data mean – Arithmetic average of data points.
Data standard deviation – Standard deviation of the distribution of data points.
Population-estimated mean – The mean value estimated from use of the assigned distribution.
Population-estimated standard deviation – The standard deviation value estimated from use of the assigned distribution.

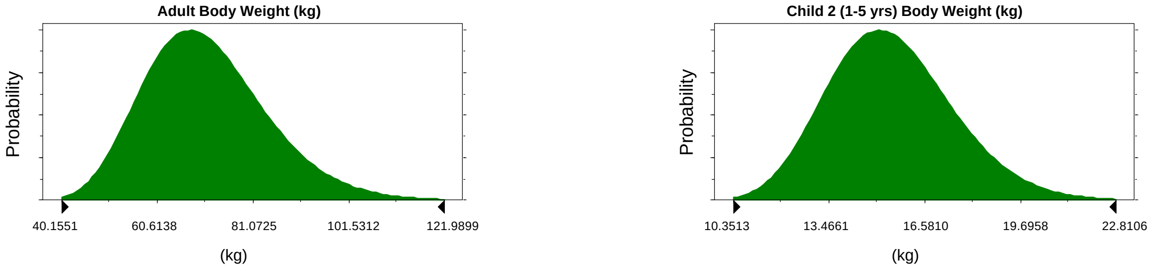

Figure 6-9. Adult and child body weight assumptions.

6.1.4 Inhalation Rate

Several inhalation rate studies are presented in the EFH. Most of these studies are short-term studies based on specific activity patterns. The study selected for developing a distribution suitable for use in risk analysis for long-term exposure was Layton (1993). This study presents a methodology for estimating metabolically consistent inhalation rates by calculating breathing rates based on oxygen consumption associated with energy expenditures for short- and long-time periods. An analysis of inhalation rate data presented in the Layton study was conducted by Myers et al. (1998). A lognormal distribution of inhalation rates was developed for age groups using the data from this study. A summary of the data analysis is presented in Table 6-15 and Figure 6-10. This statistical analysis indicates that for children younger than 3 years, the CV (the standard deviation/mean) is close to 0.7; for other age groups, this factor is close to 0.3.

Table 6-15. Inhalation Rates

Group	Distribution	Population-Estimated Mean (m^3/d)	Population-Estimated Standard Deviation (m^3/d)
Age 1 to 5	Lognormal	7.55	3.78
Adult	Lognormal	13.3	3.99

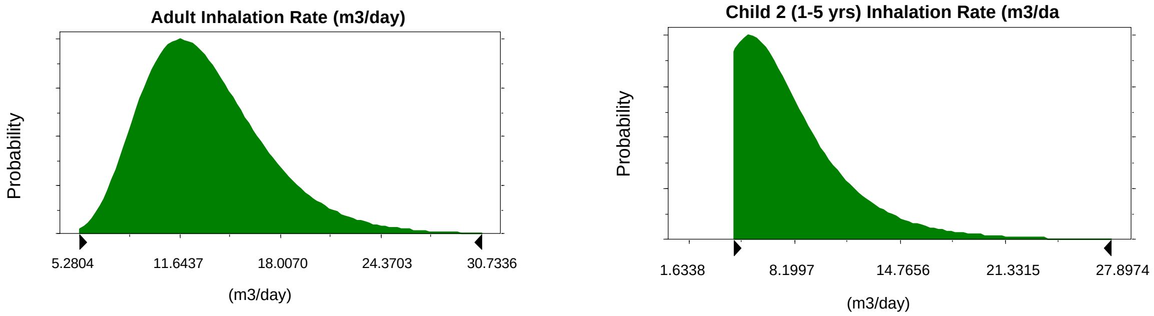

Figure 6-10. Adult and child inhalation rate assumptions.

6.2 Toxicity Assessment

The health benchmark values for metals used in this risk analysis are based on the values presented in IRIS or HEAST. The health benchmark values are documented in Appendix K.

6.2.1 Dose-Response Assessment

The dose-response assessment determines the most sensitive health effects associated with a constituent and attempts to express the relationship between dose and effect in quantitative terms. These quantitative terms are known as toxicity values, or health benchmarks. Generally, health benchmarks are developed by EPA and listed in IRIS or HEAST (U.S. EPA, 1997e). Four general types of health benchmarks are developed: reference doses (RfDs), reference concentrations (RfCs), cancer slope factors (CSFs), and unit risk factors (URFs).

RfDs and RfCs, used to evaluate noncancer effects for ingestion and inhalation exposures, respectively, are defined as “an estimate (with uncertainty spanning perhaps an order of magnitude or greater) of a daily exposure level for the human population, including sensitive subpopulations, that is likely to be without an appreciable risk of deleterious effects during a lifetime” (U.S. EPA, 1989b). RfDs are expressed in milligrams of chemical intake per kilogram body weight per day (mg/kg/d), and RfCs are expressed as milligrams of chemical per cubic meter of air (mg/m^3). RfCs may be converted into inhalation RfDs in mg/kg/d by multiplying by the inhalation rate (20 m^3/d) and dividing by the body weight (70 kg).

6.2.1.1 Carcinogens. CSFs and URFs may be derived from a number of statistically and/or biologically based models. Traditionally, the linearized multistage model has been the default model for extrapolating cancer risk estimates to low doses; however, other models have been used. Although several models may provide a good fit to the experimental data, the risk estimates at low doses may be different by several orders of magnitude. Under EPA's proposed cancer risk guidelines (*Federal Register* [FR] 61 17960), significant changes to the default methodology are proposed. Although the new methodology has been used to develop some benchmarks listed in IRIS (e.g., polychlorinated biphenyls [PCBs]), all of the cancer benchmarks used in this report are based on the linearized multistage model.

CSFs and URFs are used to evaluate cancer effects for ingestion and inhalation exposures, respectively. Unlike RfDs and RfCs, CSFs and URFs do not represent "safe" exposure levels; rather, they are expressed as an upperbound slope factor that relates levels of exposure with a probability of effect or risk. The CSF is expressed in units of (mg/kg/d)$^{-1}$ and the URF for inhalation exposures is expressed in units of (µg/m^3)$^{-1}$.

The individual risk level considered to be a level of concern is 1E-05, or an increase in cancer incidence of one case in a population of 100,000 individuals.

6.2.1.2 Noncarcinogens. RfD and RfC have been the primary benchmarks used to evaluate noncarcinogenic hazards posed by environmental exposures to chemicals and are based on a fundamental concept of toxicology: "the dose makes the poison." This is known as the threshold approach, which is based on the theory that there is a "safe" exposure level (the threshold) that must be exceeded before a toxic effect occurs.

RfDs and RfCs do not provide true dose-response information but are, essentially, estimates of an exposure level or concentration believed to be below the threshold level or no-observed-adverse-effects level (NOAEL). It also is important to understand that all RfDs are not necessarily equivalent expressions of toxicity. The degree of uncertainty and confidence levels in the various RfDs varies a great deal and is based on different toxic effects. RfDs and RfCs that have been verified by an intra-Agency workgroup are listed in IRIS.

RfDs and RfCs are derived from the highest NOAEL identified in human epidemiological studies or from subchronic (generally a 90-day study in rats and mice) or chronic studies in laboratory animals. If an NOAEL is not identified in any of the available studies, the lowest-observed-adverse-effect level (LOAEL) is used. If the studies report dose levels as parts per million (ppm) in the diet or water, the dose levels are converted into mg/kg/d based on the consumption level and body weight of the test subjects. It is generally assumed that dose levels expressed on a mg/kg/d basis are equivalent in humans and animals; therefore, dose adjustments are not necessary unless chemical-specific pharmacokinetic data indicate that a dose adjustment is appropriate. NOAELs and LOAELs are adjusted ($NOAEL_{adj}$ or $LOAEL_{adj}$) for exposure protocols that are not continuous (i.e., less than 7 days per week or 24 hours per day).

Differences in respiratory rates and respiratory physiology between humans and laboratory animals are well- recognized; therefore, NOAELs and LOAELs identified from inhalation studies are converted into the human equivalent concentration ($NOAEL_{HEC}$ or $LOAEL_{HEC}$) before deriving the RfC. The RfC methodology is described in detail in U.S. EPA (1994b).

Once a suitable NOAEL or LOAEL has been identified, the characteristics and the quality of the database are examined and the NOAEL or LOAEL is divided by uncertainty factors and modifying factors to derive the RfD or RfC. Factors of 10 are most commonly used as uncertainty factors. The default value for the modifying factor is 1. All uncertainty factors and modifying factors are multiplied together to derive the total uncertainty factor.

The individual level considered to be a level of concern is a hazard quotient (HQ) of 1. The HQ is defined as the ratio of the daily dose of a contaminant to the RfD or RfC.

6.2.2 Health Benchmarks

Sources for existing toxicological benchmarks, listed in order of preference, are EPA's IRIS and HEAST (U.S. EPA, 1997e). All published benchmark values and their sources are listed in Appendix K. EPA values are the only values used in this analysis.

6.2.2.1 Health Benchmark Values for Metals. The health benchmark values used in this risk analysis for metals were developed by EPA and are derived from the IRIS or HEAST database. These values are presented in Table 6-16.

6.2.2.2 Lead Health Benchmark. The health benchmark for lead is based on a blood lead level of 10 µg/dL blood in children aged 6 months to 7 years. This endpoint was estimated using the Integrated Exposure Uptake Biokinetic (IEUBK) Model for lead in children developed by EPA. This model uses the modeled levels of lead in soil and dietary items as inputs and estimates a probability for exceeding the blood lead limit of 10 µg/dL in young children exposed to these levels. This blood lead level has been associated with long-term adverse health effects such as neurological deficits.

Table 6-16. Health Benchmark Values for Metals in Fertilizers

Metal	RfD (mg/kg/d)	RfC	CSF Oral $(mg/kg/d)^{-1}$	Inhalation URF
Arsenic	0.0003 (IRIS)	NA	1.5 (IRIS)	0.0043 (IRIS)
Cadmium	0.001 (IRIS)	NA	NA	0.0018 (IRIS)
Chromium	0.003 (IRIS)	0.0001(IRIS)	NA	0.012 (IRIS)
Copper	NA	NA	NA	NA
Lead	NA	NA	NA	NA

Mercury[1] Elemental Divalent Methyl mercury	0.0003(HEAST) 0.0001(IRIS)	0.0003 (IRIS)	NA	NA
Nickel	0.02 (IRIS)	NA	NA	0.00024 (IRIS)
Vanadium	0.007 (HEAST)	NA	NA	
Zinc	0.3 (IRIS)	NA	NA	

6.2.2.3 **Health Benchmark Values for Dioxin Congeners**. The health benchmarks for dioxin congeners are based on the TEF methodology as presented in *Interim Procedures for Estimating Risks Associated with Exposures to Mixtures of Chlorinated Dibenzo-p-dioxins and -dibenzofurans (CDDs and CDFs) and 1989 Update* (U.S. EPA, 1989). The TEF concept is based on the fact that CDDs and CDFs constitute a family of structurally related chemical compounds. Many studies have been conducted to define the toxic effects of 2,3,7,8-tetrachlorodibenzodioxin (2,3,7,8-TCDD). Much less is known about the other congeners; however, available information has shown a mechanistic basis for the similarity in the ability to elicit a similar biological/toxic response in various in vivo and in vitro test systems. The TEF approach uses this information to establish a relationship between the toxicity of each congener and TCDD. The factor used to express this relationship is the TEF. The TEF for each congener considered in this risk assessment is presented in Table 6-17. This factor is used to estimate the health benchmark for the congener with respect to the toxicity of TCDD.

Table 6-17. TEF and Health Benchmarks for Dioxin Congeners

CAS Number	Dioxin Congener	TEF	CSF Based on TEF $(mg/kg/d)^{-1}$
1746016	TCDD, 2,3,7,8-	1	156000
3268879	OCDD, 1,2,3,4,5,7,8,9-	0.0001	15.6
19408743	HxCDD, 1,2,3,7,8,9-	0.1	15600
39001020	OCDF, 1,2,3,4,6,7,8,9-	0.0001	15.6
39227286	HxCDD, 1,2,3,4,7,8-	0.1	15600
40321764	PeCDD, 1,2,3,7,8-	1	156000
51207319	TCDF, 2,3,7,8-	0.1	15600

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[1] . The agency did not use the methodology most recently recommended in the final Mercury Report to Congress (RTC). (USEPA, 1998b) Instead, for this assessment, EPA uses a relatively simple, less sophisiticated, less resource intensive model to screen for potential hazards due to mercury cycling in the waterbody and subsequent exposure through fish ingestion.

55673897	HpCDF,1,2,3,4,7,8,9-	0.01	1560
57117314	PeCDF, 2,3,4,7,8-	0.5	78000
57117416	PeCDF, 1,2,3,7,8-	0.05	7800
57117449	HxCDF, 1,2,3,6,7,8-	0.1	15600
57653857	HxCDD, 1,2,3,6,7,8-	0.1	15600
60851345	HxCDF, 2,3,4,6,7,8-	0.1	15600
67562394	HpCDF,1,2,3,4,6,7,8-	0.01	1560
70648269	HxCDF, 1,2,3,4,7,8-	0.1	15600
72918219	HxCDF, 1,2,3,7,8,9-	0.1	15600
99999999	HpCDD, 1,2,3,4,6,7,8,-	0.01	1560

These TEF factors may also be used to estimate concentrations of constituents in media in terms of TCDD toxicity equivalency quotients (TEQs). This method allows the comparison of exposure point concentrations for mixtures of different congeners. In this risk assessment, the media concentrations of dioxins and furans are expressed as TEQs for comparison among products and climate regions.

7.0 Risk Characterization

This section summarizes the results of the probabilistic risk analysis evaluating the risks from 9 metals and 17 dioxin congeners contained in each off 13 fertilizer products. The U.S. Environmental Protection Agency's (EPA's) waste program generally defines risk levels of concern for carcinogens as risks of $1x10^{-5}$ (1 in 100,000) or greater at the upper end of the risk distribution (e.g., 90th or 95th percentile). The level of concern for noncancer effects is generally indicated by a hazard quotient (HQ) of 1 or greater at the upper end of the distribution. Therefore, the risk results presented in this section are those potential cancer risks of $1x10^{-5}$ or greater and noncancer hazards with HQ equal to or greater than 1 at the 90th percentile of the risk distribution.

The risk results are presented in terms of individual lifetime risk to the farmer and farm child. Farm child risks are based on evaluation of exposures to 1- to 5-year-old children. For this analysis, these individuals are assumed to consume homegrown produce and home-produced beef and dairy products from fertilized fields and fish caught from streams adjacent to amended agricultural fields. These individuals are also assumed to incidentally ingest soil amended with fertilizer products. Adult farmers or farmer workers are assumed to directly ingest fertilizer products on the days when fertilizers are being applied.

The risks for all indirect ingestion pathways for a single constituent are assumed to be additive. Ingestion exposures are assumed to occur in the same time frame for the same individuals, and the same health benchmark is assumed to be applicable to all ingestion exposures. For constituents with noncancer endpoints, inhalation exposure is additive to ingestion exposure only if the same human health benchmark endpoint is applicable to both pathways. Similar additions of risk may be made for different metals in the same product. For metals, however, only arsenic is considered a carcinogen by the oral route. All other metals are not carcinogenic by the oral route and do not have common health benchmark endpoints; thus, ingestion exposures to different metal constituents are not considered additive. No metal inhalation exposures are considered additive because there are no common target organs for the noncancer human health benchmarks.

A summary of the overall risk results from direct (incidental ingestion of fertilizer and/or fertilizer amended soil) and indirect (food chain) pathways for all fertilizers evaluated is provided in Table 7.1 below. A more detailed presentation of the the 50^{th} and 90^{th} percentile risk results for metals and dioxins for those fertilizers showing risks of concern is provided in Sections 7.1 - 7.3. The media concentrations and corresponding risks for the 50th, 90th, 95th, and 99th percentiles of the risk distribution for each exposure pathway and for each product and climate region combination are presented in Appendix L.

Constituents Showing Potential Cancer Risks ≥1E-05 or HQ ≥1 at the 90th Percentile from Application of Fertilizer Products by Pathway

	Constituent																			
Fertilizer Product	**As**		**Cd**		**Cr**		**Cu**		**Pb**		**Hg**		**Ni**		**Vn**		**Zn**		**Dioxins**	
	Pathway																			
	D[1]	**I**[2]	**D**	**I**	**D**	**I**	**D**	**I**	**D**	**I**	**D**	**I**	**D**	**I**	**D**	**I**	**D**	**I**	**D**	**I**
Phosphate (P2O2)	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
NPK for Phosphorus	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
NPK for Nitrogen (N)	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
Potash (K2O)	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
Sulfur (nutrient)	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
Sulfur (pH)	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
Lime (CaCO3)	1 of 10[3]	1 of 10	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	1 of 2
Gypsum	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
Iron	1 of 3	1 of 3	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
Boron	1 of 2	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
Manganese	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no
Zinc	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	1 of 12
Micronutrient Mixes	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no	no

[1] "D" **-** Direct ingestion pathways; includes incidental ingestion of fertilizer product during application and/or incidental ingestion of soil amended with fertilizer

[2] "I" **-** Indirect or food chain pathway; includes ingestion of contaminated fruits, vegetables, beef, dairy and fish products.

[3] Number of samples that have constituent concentrations that pose a risk ≥ 1E-5 or hazard quotient ≥ 1 out of total number of samples evaluated

7.1 Risk Results for Metal Constituents in Fertilizer Products

Table 7-2 shows metals from fertilizer application that may present potential cancer risks or non-cancer hazards of concern at the 90th percentile of the risk distribution based on the results of this risk analysis.

7.1.1. Food Chain Pathway

Arsenic is the only metal for which indirect pathway risks of concern are indicated. The food chain analysis estimates increased cancer risk from arsenic at the 90th percentile for the farmer and farm child for liming agents and iron micronutrients.

Liming Agents—Arsenic concentration data were available for 10 samples of liming agents. The food chain ingestion risks are driven by a single sample with a high arsenic concentration and a low calcium carbonate equivalent content. This sample contains only 7.6 percent calcium carbonate and has the highest concentration of arsenic of any sample (48 mg/kg). Up to 10 times more of this product must be applied to achieve the same liming effect as most other products. This sample accounts for all risk in excess of 1E-05.

Iron Micronutrients—Only three samples of iron micronutrient products are provided in the OPPT Report. Each sample has significantly different concentrations of arsenic (2.5, 34.5, and 4,950 mg/kg). All indirect risk estimated for iron micronutrients is attributable to the single high arsenic concentration.

7.1.2 Direct Ingestion Pathway

Table 7-2 also shows metals from fertilizer application that may present potential cancer risks or noncancer hazards of concern at the 90th percentile of the risk distribution from direct ingestion exposure pathways based on the results of this risk analysis. The direct ingestion pathway includes ingestion of fertilizer amended soil for both the adult and child farm resident and direct ingestion of fertilizer by the farmer or farm worker during days when fertilizer is being applied. For the direct ingestion pathway, risks of concern at the 90th percentile are estimated for only one of the metals evaluated for this assessment: arsenic. For direct ingestion of fertilizer products, arsenic exceeds a 90th percentile risk of 1E-05 for the adult farmer or farm worker resulting from application of iron micronutrients and boron micronutrients to the agricultural field. Risks of concern are not found for either the adult farmer or child of farmer from to ingestion of fertilizer amended soil.

Iron Micronutrients—Only three samples of iron micronutrient products are provided in the OPPT Report (U.S. EPA, 1998). Each sample has significantly different concentrations of arsenic (2.5, 34.5, and 4,950 mg/kg). All direct ingestion risk estimated for iron micronutrients is attributable to the single high arsenic concentration.

Boron Micronutrients—Only two data points for arsenic concentrations are provided in the OPPT Report for boron micronutrient products (1 and 1,040 mg/kg). All incidental ingestion risk estimated for this product type is attributable to the single high arsenic concentration.

Table 7-2. Metals Showing Potential Cancer Risks ≥1E-05 or HQ ≥1 at the 90th Percentile from Application of Fertilizer Products

			Child of Farmer		Adult Farmer	
Metal	**Product**	**Pathway**	**Maximum 50% Risk**	**Maximum 90% Risk[1]**	**Maximum 50% Risk**	**Maximum 90% Risk**
Arsenic	Liming agents	Total food chain	4E-07	1E-05	1E-06	6E-05
	Iron micronutrients	Total food chain[2]	4E-08	1E-05	1E-07	5E-05
	Iron micronutrients	Incidental Ingestion[3]	NA[4]	NA	2E-07	4E-05
	Boron micronutrients	Incidental Ingestion	NA	NA	5E-06	9E-05

1 Highest 90th percentile risk for all of the 29 climate regions. Variations in climate region affect indirect risk pathways only. Indirect 90th percentile risks vary only slightly among climate regions.
2 Total food chain includes all pathways evaluated except direct ingestion of fertilizer and fertilizer amended soil; this includes includes ingestion of contaminated fruits, vegetables, beef, dairy and fish products.
3 Incidental ingestion includes direct ingestion of fertilizer product during application.
4 Direct ingestion during application is not evaluated for the child of farmer

7.2 Risk Results for Dioxin and Furan Congeners from Application of Fertilizer Products

Risks from dioxins are estimated for seven fertilizer products. Table 7-3 presents a summary of dioxin risks of concern from the application of fertilizer products. The risks for all pathways for dioxins are assumed additive. Exposures are assumed to occur in the same time frame for the same individuals, and the same health benchmark is assumed to be applicable to all ingestion exposures. Risks due to exposure to all dioxin and furan congeners are based on the toxicity equivalent factor (TEF) methodology presented in Section 6.0 and are assumed to be additive across all congeners and pathways.

Only liming agents and zinc micronutrient fertilizers exceed a risk level of 1×10^{-5} for dioxins at the 90th percentile. All other products presented no risk greater than 1×10^{-5} at the 90th percentile. These results are based on the constituent concentration data available from the Washington State report and on application practices described in the OPPT report (U.S. EPA, 1998).

Dioxin congeners were measured in only three samples of liming agents in the Washington State report (Rogowski and Golding, 1998). One sample had no detectable dioxins; of the other two, one had a total toxic equivalency quotient (TEQ) concentration five-fold higher than the other. Because no application rates were reported in the Washington state report, application rates and frequencies reported in the OPPT document for liming agents are assumed for products in the Washington report. As previously noted, the application rate distribution for liming agents includes applications rates that exceed typical rates for liming agents based on a lime sample with low $CaCO_3$ content provided in the OPPT report. Consequently, risks from dioxins in liming agents may be overestimated.

There are limited samples for most product categories with the exception of zinc micronutrients, for which there are 12 samples. There is a large range of TEQ concentrations in zinc micronutrients (<1 to >900 ppt). The sample with the highest TEQ is approximately twice the concentration of the next highest sample; thus, most risk is due to the single high concentration sample.

Table 7-3. Summary of Maximum 90th & 50th Percentile Risk from Dioxins from Application of Fertilizer Products

		Child of Farmer		Adult Farmer	
Product	**Pathway**	**Maximum 50% Risk**	**Maximum 90% Risk**	**Maximum 50% Risk**	**Maximum 90% Risk**
Liming agents	Total food chain	5E-05	3E-04	9E-05	9E-04
Zinc micronutrient	Total food chain	1E-07	9E-06	2E-07	1E-05

7.3 Ecological Risk Screening for Metals from the Application of Fertilizer Products

As a preliminary screening tool, the metal concentrations in a waterbody adjacent to a field where fertilizer products may be applied were compared to chronic ambient water quality criteria. This comparison is presented in Table 7-4. No exceedances of water quality criteria are projected.

Table 7-4. Comparison of Maximum Concentrations of Metals in Waterbody from Application of Fertilizer Products to Chronic Ambient Water Quality Criteria

Metal	Chronic Ambient Water Quality Criteria Limit (mg/L)	Concentration in Waterbody due to Fertilizer Application (mg/L)	Products that Exceed Criteria
Arsenic	0.150	0.00149	None
Cadmium	0.01036	0.00259	None
Chromium (VI)	0.01143	0.00192	None
Copper	0.00938	0.00203	None
Lead	0.00316	0.000259	None
Mercury	0.00091	NA (model uncertainty)	None
Nickel	0.05216	0.00000469	None
Vanadium	NA	NA	None
Zinc	0.1217	0.00452	None

NA = Not available.

7.4 Conclusions

This risk assessment was conducted using available metal and dioxin concentration data for 13 types of fertilizer products. Based on the limited data available, most fertilizers do not pose harm to human health or the environment. Risks of concern from fertilizer products can be attributed to arsenic and dioxins found in select liming agents and micronutrients. Cancer risks exceeding 1×10^{-5} (1 in 100,000) are estimated for arsenic by both direct and indirect or food chain pathways. Risks of concern from dioxin congeners are attributable soley to food chain pathways.

Risks estimated in this assessment are for the farmer and the farm child, individuals within the general population most likely to be highly exposed to hazard constituents in fertilizers. Farmers and their children are assumed to consume a large portion of exposed vegetables, exposed fruits, root vegetables, and beef and dairy products from homegrown sources amended with fertilizer products. These receptors also are assumed to ingest amended soil, to inhale vapors and particles from windblown emissions and emissions occurring during the application of fertilizer products. Adult farmers and farm workers are assumed to ingest fertilizer products incidentally on the days that fertilizers are applied. The risks estimated using these high-exposure assumptions should reasonably demonstrate the limit for risk to all receptors. All other receptors (adult and child residents, recreational fishers, and home gardeners) are expected to have lower exposures through fewer pathways and, thus, lower risk than the farmer and his/her child.

8.0 Uncertainty

Previous sections of this document present the data, assumptions, and models used to develop risk estimates for the application of fertilizer products to agricultural fields. This section qualitatively addresses the primary sources of uncertainty within the risk assessment and the effects this uncertainty has on interpreting the results.

Uncertainty is inherent in the risk assessment process. It occurs because the risk assessment process is complex, and variability is inherent in the environment. The sources of uncertainty may be classified as parameter uncertainty and variability, exposure scenario uncertainty, and model uncertainty. Parameter uncertainty occurs when parameters appearing in equations cannot be measured precisely and/or accurately. Variability refers to the normal variations in physical and biological processes that cannot be reduced with additional data. Variability in this risk assessment has been addressed by using a probabilistic analysis. Exposure scenario uncertainty occurs because of the inability to measure exposure of receptors to constituents of concern. Model uncertainty is associated with all models used in risk assessment and occurs because computer models require simplifications of reality. These computer models exclude some variables and interactions that influence fate and transport but that cannot be included due to complexity or lack of data. Each of these issues is described below.

8.1 Parameter Uncertainty

Parameter uncertainty occurs when parameters appearing in equations cannot be measured precisely and/or accurately. In the fertilizer risk assessment, there are many sources of parameter uncertainty.

8.1.1 Product Characterization

Product characterization, which includes assumptions regarding fertilizer composition and use, is a primary source of uncertainty in this risk assessment.

8.1.1.1 Constituent Composition. Data used in this risk assessment on levels of contaminants in fertilizers are limited to information on metals levels provided in the *Draft Final Report: Background Report on Fertilizer Use, Contaminants and Regulations* (U.S. EPA, 1998) and information on levels of dioxin contained in the *Screening Survey for Metals and Dioxins in Fertilizers, Soil Amendments, and Soils in Washington State* (Rogowski and Golding, 1998). However, fertilizer products are frequently blended locally to meet specific local soil and crop requirements. This practice introduces much variability into the characterization of fertilizer products, even for those products for which numerous samples have been obtained for use in this analysis. For products having limited samples, such as some of the micronutrient products, there is great variability among the limited number of samples available. The probabilistic analysis has been used to address variability to the extent possible. However, given the limited data available for some of the products assessed, this approach is not adequate to fully characterize the variability in the constituent concentration within a product. For example, for products for which there are only few samples and the range of metal concentrations spans several orders of magnitude, it is not possible to identify representative metals concentrations for those products. For example, for the product type of iron micronutrients, there are only three samples. All risk due to arsenic in this product is attributable to a single sample containing 4,950 mg/kg of arsenic, which is several orders of magnitude greater than the other 2 samples that contain 2.5 mg/kg and 34.4 mg/kg arsenic, respectively. With so few samples and so large a difference in measured constituent concentrations, much uncertainty is associated with this product characterization.

8.1.1.2 Application Rate and Frequency. Additions of contaminants to the soil are estimated based not only on concentrations measured in the products but also the application rate and frequency of these products. For the purposes of this analysis, the distribution of application rates are based on the data presented in the Office of Pollution Prevention and Toxics (OPPT) report (U.S. EPA, 1998) for the 50th, 85th, and 95th percentile application rate for each product. No distinctions in the document are made to account for specific soil conditions or crop types. These simplifying assumptions introduce additional uncertainty into the analysis. Practically, fertilizer application is adjusted locally based on soil conditions and specific crop requirements. However, it is not possible to account for these site-specific adjustments in a nationwide risk assessment. In this analysis, all types of fertilizer products are assumed applied to all crop types at all application rates reported in the OPPT document. This is a conservative approach because the highest application rates are assumed for all crop types in all locations and soil conditions. This strategy ensures that most specific geographic and crop variations are included within the range of application rates and frequencies considered but does not eliminate uncertainty associated with these parameters.

There is additional uncertainty associated with the application rates and frequencies assumed for estimating risks from dioxin congeners because no application rates were reported in the Washington state report. In order to estimate dioxin risks, application rates and frequencies reported in the OPPT document for similar products are assumed for products in the state of Washington report. This introduces uncertainty associated with the assignment of products to the appropriate product type. If the product type is not easily identified, the product is not evaluated in the analysis.

There is also uncertainty regarding application assumptions used to estimate risk from the direct ingestion pathway and in the estimation of particle emissions due to spreading and tilling. For this assessment, fertilizer applications are assumed to occur on 16 days per year for primary nutrient fertilizers (California Department of Food and Agriculture, 1998) and 8 days per year for micronutrient fertilizers (The Fertilizer Institute [TFI], 1999). These parameters are not varied due to lack of additional data. These assumptions are intended to be protective but within normal practices.

Additionally, only a single product is assumed to be applied to a single field. No multiple product applications are modeled in this risk assessment, although this practice is known to occur frequently to meet specific soil improvement requirements for particular crops. Therefore, risks may be underestimated because of this assumption.

8.1.1.3 Agricultural Field Size. Only a single agricultural field size, the 90th percentile field size from a nationwide distribution of farm sizes, is evaluated for this analysis. Portions of the analysis that are affected by this choice are the air dispersion and redeposition on the field and to the adjacent waterbody and the mass of soil erosion to the adjacent stream. These affected pathways are positively related to field size. Consequently, risk through these pathways will be somewhat overestimated. Fertilizers are assumed to be applied at a mass per unit area basis so that soil loadings are not affected by field size.

8.1.1.4 Soil Parameters.

8.1.1.4.1 *Soil Distribution Coefficients (K_ds)*. The soil data used in this analysis are specific for each area evaluated within a climate region. However, many important soil conditions cannot be included in the simplistic models available for this analysis. The effect of complex interactions among soil parameters on metals speciation are addressed only indirectly in this risk assessment through the use of empirically derived soil-water distribution coefficients (K_ds). This is believed to be a valid approach in that varying interactions among critical soil parameters, such as pH, clay content, and cation exchange capacity, ultimately affect the K_ds.

The pH is among the most important factors influencing metals speciation. In order to consider pH appropriately in the analysis, a range of empirically derived soil K_ds for each metal was collected from the literature. The data set was then culled so that the K_ds remaining in the distribution represented only soil systems within the pH range and soil types considered appropriate for agricultural use (pH 4 to 9). However, insufficient numbers of data points and information about the soil systems associated with the studies are available to link specific K_ds collected from the literature to a specific soil pH for use in the risk analysis. Therefore, K_ds for metals are matched randomly with soils in this modeling effort. Consequently, while this approach is likely to cover the range of complex soil interactions, much uncertainty remains in this area.

8.1.1.4.2 *Soil to Plant Uptake of Metals*. Soil-to-plant uptake factors for metals are also a source of uncertainty. The range of plant biouptake values (Br) is large and represents numerous plant types. For this analysis, Br values are estimated using empirical data from the literature. Only plant uptake values derived from field studies for the crop types assessed are used. Variation among plant biouptake values is addressed by using a distribution of these empirically derived values in the probabilistic methodology. However, many issues concerning plant uptake are not addressed. One of the most important is competition among metals for soil binding sites. Metals competition is not considered in this risk assessment. Rather, each metal is considered independently. In general, the competition of multiple metals for available sorption sites results in higher dissolved metal concentrations. In particular, interactions between zinc and cadmium have been studied and are known to influence the uptake of cadmium from the soil. A high zinc-to-cadmium ratio inhibits the uptake of cadmium into plants and animals, but as the cadmium concentration rises in relationship to zinc, cadmium is taken up preferentially by plants (Chaney, 1999), raising the hazard associated with cadmium in the food chain. The inability to account for interaction among metals in the soil system adds uncertainty to the analysis, and risks may be overestimated.

Additional uncertainty is introduced in the data used to develop plant uptake factor distributions. In particular, uncertainty arises due to the use of data from plants grown on nonagricultural sites. An expanded plant uptake database was developed especially for this analysis as described in Section 5.2.2. The objective was to acquire a large enough data set to develop Br distributions for all of the metals of concern and for all of the plant categories included in the model. The resultant data set includes metal concentrations for a wide variety of plant species grown in a variety of site conditions. Under normal growing conditions, plants can potentially accumulate concentrations of some metal ions orders of magnitude greater than concentrations in the surrounding medium (Raven et al., 1982). On the other hand, uptake of some metals appears to be saturation-limited. Still other metals that are also plant nutrients are taken up only as needed; therefore, concentrations do not vary relative to the soil concentration (Sample et al., 1997). Since plant uptake rates are a function of so many complex, interrelated variables, an ideal data set for developing Br distributions would closely mirror the actual conditions under which exposure to fertilizer contaminants occurs (i.e., data consisting exclusively of concentrations measured from agricultural crops grown on soils amended with conventional agricultural fertilizers). The inclusion of uptake data from plants grown in nonagricultural settings increases the level of uncertainty inherent in the risk assessment. The database includes some data from contaminated sites. Both the Oak Ridge National Laboratory [ORNL] sources (Bechtel Jacobs, 1998; Sample et al., 1997) focus on wildlife exposure and therefore include data for noncrop species and from nonagricultural settings. The source of metal contamination in some studies is industrial pollution or sources other than fertilizer application.

It is not clear to what extent the inclusion of these data may bias the risk results. An example analysis was performed to compare the mean Br values with and without data from contaminated sites. The arsenic Br values for forage were chosen for the analysis since these data include two contaminated study sites with very high soil concentrations of arsenic. The mean BR values are the following:

#	Mean Br with contaminated site data: 7.39E-02
#	Mean Br without contaminated site data: 9.45E-02

Likewise, a comparative analysis was done excluding all of the data from the ORNL (Bechtel Jacobs, 1998) report. These data represent the most discreet subset of substantially non-agricultural data. The results for the most affected categories are shown in Table 8-1.

Table 8-1. Comparison of Plant Soil Uptake Factors (Brs) Using Full Data Set and Without ORNL Data

Most Affected Data Categories	Mean Br for Full Data Set	Mean Br Excluding ORNL (Bechtel Jacobs, 1998) Data
Arsenic - Herbage	6.53E-02	6.88E-02
Arsenic - Roots	9.85E-02	9.86E-02
Cadmium - Forage	9.22E-01	1.12E+00

Additional anomalies in the data were noted during peer review. For example, the arsenic uptake data for roots includes primarily data on potatoes. Nine of the 16 observations for potatoes report arsenic concentrations in the peels, while the remaining observations report concentrations in the flesh or pulp. Several of the concentrations in potato peels are orders of magnitude higher than the highest concentration reported for potato pulp. Moreover, it is generally known that some contaminants are sequestered in outer layers or peels of some foods. Thus, the inclusion of a preponderance of peel data is a potential source of uncertainty for the uptake of arsenic in root crops and the risk from arsenic from the ingestion of root vegetables may be overestimated.

8.1.1.5 Toxicological Benchmarks. Sources of uncertainty in toxicological benchmarks include extrapolations of responses at high experimental doses of a contaminant under controlled conditions to low doses under highly variable environmental conditions and adequacy of the database (e.g., number of studies available, toxic endpoints evaluated, exposure routes evaluated, sample sizes, length of study).

8.1.1.5.1 *Carcinogens*. The carcinogenic constituents of concern in this risk assessment include arsenic, hexavalent chromium, and dioxins. Arsenic and hexavalent chromium (inhalation only) are known human carcinogens. Dioxins are considered probable human carcinogens.

EPA estimates the risk of developing cancer from the estimated lifetime average daily dose and the slope of the dose-response curve. A cancer slope factor (CSF) is derived from either human or animal data and is taken as the upper bound on the slope of the dose-response curve (generally assumed to be linear) in the low-dose region. The CSF is expressed as a lifetime excess cancer risk per unit exposure. CSFs can vary by several orders of magnitude, depending on the extrapolation model used. A limited understanding of cancer biology in laboratory animals and humans adds to the uncertainty of identifying true human carcinogens.

Total carcinogenic risk is determined for each receptor population assuming additivity. The same approach is used for estimating cancer risks in both adults and children for this assessment. Exposure factors were modified for children to account for the differences between adult and children receptors (e.g., body weight, exposure duration). However, significant uncertainties and unknowns exist regarding the estimation of lifetime cancer risks in children. Methodologies for estimating environmental threats to children's health are relatively new. They are currently being debated within the scientific community, and will continue to evolve. Therefore, significant uncertainties and unknowns exist regarding the estimation of lifetime cancer risks in children. In addition, the method of estimating cancer risks in children used in this analysis has not been externally peer-reviewed.

Dioxin risk assessment is particularly complicated and controversial because of the numerous congeners that make up a dioxin sample. A toxicity equivalency factor (TEF) methodology is used to develop risk estimates for individual congeners and to estimate a total dioxin risk.

Issues associated with the chromium risk estimates presented in this document include the assumption that all chromium is in the hexavalent form. Hexavalent chromium is much more toxic than the trivalent form; however, the trivalent form is much more common and stable in the environment. Therefore, risks from chromium are almost certainly overestimated.

8.1.1.5.2 ***Noncarcinogens***. Much uncertainty is also associated with the noncancer health benchmarks or reference doses (RfDs) for oral exposures and the reference concentrations (RfCs) for inhalation exposures. RfDs and RfCs may include the following uncertainty factors:

- A 10-fold factor is applied when extrapolating from valid experimental results in studies using prolonged exposure to average healthy humans. This factor is intended to account for the variation in sensitivity among the members of the human population and is referenced as “10H.”

- A 10-fold factor is used when extrapolating from valid results of long-term studies on experimental animals when results of studies of human exposure are not available or are inadequate. This factor is intended to account for the uncertainty involved in extrapolating from animal data to humans and is referenced as “10A.”

- A 10-fold factor is used when extrapolating from less than chronic results on experimental animals when there are no useful long-term human data. This factor is intended to account for the uncertainty involved in extrapolating from less than chronic no-observed-adverse-effect levels (NOAELs) to chronic NOAELs and is referenced as “10S.”

- A 10-fold factor is used when deriving an RfD from a lowest-observed-adverse-effect level (LOAEL), instead of a NOAEL. This factor is intended to account for the uncertainty involved in extrapolating from LOAELs to NOAELs and is referenced as “10L.”

- A modifying factor (MF) is an additional uncertainty factor that is greater than 0 and less than or equal to 10. Professional judgment is used to determine the appropriate MF. The magnitude of the MF depends on the professional assessment of scientific uncertainties of the study and the database not explicitly treated above (e.g., the completeness of the overall database and the number of species tested).

The default value for the MF is 1. The uncertainty and modifying factors applied to the RfDs for metals in the fertilizer risk assessment are presented in Table 8-2.

In general, toxicologic benchmarks are designed to be conservative (i.e., overestimate risk) because of the uncertainties and challenges associated with condensing all available toxicity data into a single quantitative expression. Therefore, use of the current toxicological benchmarks most likely overestimates risks for the pathways evaluated.

Table 8-2. Uncertainty and Modifying Factors Associated with RfDs for Metals

Metal	RfD (mg/kg/d)	Uncertainty Factor	Modifying Factor	Source
Cadmium	1E-3 (food)	10	1	IRIS
Chromium VI	3E-3	300	3	IRIS
Mercury				
Mercuric chloride	3E-4	1000	1	IRIS
Methyl mercury	1E-4	10	1	IRIS
Nickel	2E-2	300	1	IRIS
Vanadium	7.0E-03	100	1	HEAST
Zinc	IRIS	3	1	IRIS

8.2 Exposure Scenario Uncertainties

Exposure modeling relies heavily on default assumptions regarding population activity patterns, mobility, dietary habits, body weights and other factors. Risk estimates presented in this document address hypothetical chronic exposures for various receptors over a realistic range of potential scenarios. The *Exposure Factors Handbook* (EFH) (U.S. EPA, 1997a, 1997b, 1997c) provides the current state of the science regarding exposure modeling and assumptions and is used throughout this document. To the extent that actual exposure scenarios vary from the assumptions used in this risk assessment, risks could be underestimated or overestimated.

8.3 Model Uncertainty

Model uncertainty is associated with all models used in all phases of a risk assessment. These include the models used to assess toxicity as well as the computer models used to predict the fate and transport of chemicals in the environment. Computer models are simplifications of reality, requiring exclusion of some variables that influence predictions but that cannot be included in the models due either to increased complexity or to a lack of data. Fate and transport models are based on numerous assumptions, simplifications, and an incomplete understanding of the factors involved.

The models used in this risk assessment were selected based on science policy and professional judgment. The air dispersion and deposition models and the indirect exposure models are used because they provide the information needed for this analysis and are generally considered by EPA to be state-of-the-science models. The partitioning model has been peer-reviewed in the context of the cement kiln dust (CKD) risk assessment upon which this assessment is based. It has been slightly revised in response to the peer review. Even though the models used in this report have been widely used and accepted, they remain a significant source of uncertainty that could result in underestimating or overestimating risk.

9.0 Comparison of EPA's Fertilizer Risk Assessment with Comparable Standards and Assessments

Both the state of California and Canada have undertaken efforts to identify and limit potential risks from the use of fertilizers. Standards developed by the Canadian Food Inspection Agency regulate levels of metals in all fertilizers and soil supplements sold in Canada. The state of California recently conducted a study (1998) to assess potential risks from arsenic, cadmium, and lead in fertilizers used commercially in California. The California assessment provides risk-based concentrations (RBCs) for lead, cadmium, and arsenic in fertilizers and micronutrients. In addition, the U.S. Environmental Protection Agency (EPA) regulates the use of sewage sludge that is applied to the land. EPA's sewage sludge standards set RBC limits for metals in sewage sludge that is used to condition soil or fertilize crops. This section provides a brief summary of the scope and purpose of each of these efforts, describes the methodology used to derive standards, and identifies key similarities and differences between these efforts and the fertilizer assessment described in this document.

9.1 California Risk-Based Concentrations

The California Department of Food and Agriculture (CDFA) recently contracted with Foster Wheeler Environmental Corporation to conduct an assessment of risk from cadmium, arsenic, and lead in fertilizers distributed commercially in California. The stated purpose of the assessment is to develop RBCs (i.e., concentrations that are considered to be protective of human health) for arsenic, cadmium, and lead in fertilizers. The study was completed and made publicly available in March 1998 (CDFA, 1998). As stated in the California report, the RBCs are intended for use by CDFA and the fertilizer industry as benchmarks for judging potential risks to human health and the environment associated with generally accepted commercial use of inorganic fertilizers. The following discussion describes key similarities and differences between the California and EPA fertilizer assessments.

9.1.1 General Comparison of Risk Methodology and Modeling Assumptions

The California study includes a screening assessment of risks from fertilizers that was conducted using a deterministic risk assessment methodology. However, the primary analysis used to derive California's RBCs for lead, cadmium, and arsenic in fertilizers was conducted using a probabilistic approach. Only the probabilistic analysis used to set RBCs is reviewed here as a basis for comparison with the EPA analysis.

The probabilistic methodology described in the California report is generally consistent with that used by EPA in its risk assessment. A fundamental difference between the EPA and California assessments is in the outcome or results that they are designed to produce. The California assessment is designed specifically to establish RBCs for arsenic, lead, and cadmium in fertilizers and micronutrients used within the state. RBCs, as defined in the study, are "the amount (or concentration) of arsenic, cadmium, or lead that can be present in commercially available inorganic fertilizers that, below which, do not pose a theoretical upper-bound unacceptable risk to human health."[1] In other words, the California study is expressly intended to determine what concentrations of metals can be present in fertilizers without posing undue risk to human health. In contrast, the purpose of the EPA assessment is to estimate the distribution of individual lifetime risk to persons exposed to hazardous constituents in fertilizers. In essence, EPA's study forward-calculates potential risks from fertilizers based on concentrations of metals present in fertilizers while the California study back-calculates concentrations of metals that may be present in fertilizers without presenting unacceptable human health risks. California's RBCs are derived and reported separately for micronutrient products and for phosphate-containing fertilizers.

EPA's assessment is broader than California's in that EPA looked at risks from nine metals and dioxin congeners in fertilizers while California's analysis was limited to three metals. Both the EPA and California assessments are based on an evaluation of a variety of fertilizers and micronutrients. Receptors considered in the California assessment include the farm worker, resident farm adult, and resident farm child. California's risk assessment includes all the exposure pathways considered in EPA's assessment, as well two additional pathways: dermal contact with fertilizers and dermal contact with surface waters. Neither of these dermal pathways are used to establish California's RBCs since the risks from other pathways are greater.

California determines its application rate and frequency distributions based on three primary crop categories: roots, vegetables, and grains. EPA's application parameter distributions are categorized based on the product type as presented in the Agency's Office of Pollution Prevention and Toxics (OPPT) *Draft Final Report: Background Report on Fertilizer Use, Contaminants and Regulations* (1998). The California study uses statewide data to define fertilizer application rate and frequency distributions for each of the three categories of crops assessed. Application parameter distributions used in EPA's analysis are developed based on nationwide data. Similarly, the California study uses statewide data to determine distributions for soil and climate parameters while EPA uses nationwide data to generate distributions for these parameters. For application duration (i.e., the number of years over which fertilizers are assumed to be continuously applied to the soil), California uses the amount of time estimated for each metal to reach equilibrium in the soil. For arsenic and cadmium, time-to-equilibrium is determined to be 50 years. For lead, time-to-equilibrium is calculated to be about 200 years. The EPA assessment assumes 100 years of fertilizer application for all constituents, although time-to-equilibrium is also calculated and considered as a component of EPA's assessment. EPA's estimates for time-to-equilibrium for lead, cadmium, and arsenic are consistent with California's.

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[1] California uses "the mid-point of EPA's acceptable risk range to define unacceptable risk as a theoretical upper-bound incremental cancer risk greater than 1 x 10^{-5} (one in 100,000) and a theoretical non-cancer level greater than a hazard index (HI) of 1.0" (CDFA, 1998).

The California and EPA analyses use the same human health toxicity values to assess carcinogenic and noncarcinogenic potency of lead, cadmium, and arsenic. Both California and EPA rely on data provided in versions of EPA's recently revised *Exposure Factors Handbook* (EFH) (1997a, 1997b, 1997c) to develop the exposure factor parameter distributions (e.g., ingestion rates, exposure frequency and duration.) Consequently, exposure factor assumptions are generally consistent between the two studies.

Constituent concentration distributions used in EPA's analysis are developed from data compiled by the Agency's OPPT in its *Draft Final Report: Background Report on Fertilizer Use, Contaminants and Regulations* (1998) and data compiled in Washington state's *Screening Survey for Metals and Dioxins in Fertilizers, Soil Amendments, and Soils in Washington State* (Rogowski and Golding, 1998) . Because California back-calculates protective RBCs rather than estimating potential human health risks based on levels of hazardous constituents contained in fertilizers, data on concentrations of metals in fertilizers are not needed to conduct the California assessment.

The California and EPA assessments generally use the same or similar models to simulate fate and transport of contaminants in soil due to use of fertilizers. EPA uses equations developed by Jury et. al. (1983, 1984, 1990) to determine contaminant loss due to degradation, volatilization, leaching, and rainwater runoff. California uses the same or equivalent equations to estimate contaminant loss via these mechanisms. Both EPA and California use the universal soil loss equation (USLE) to estimate soil erosion and overland transport of sediment from agricultural fields across intervening areas to nearby waterbodies. EPA's *Compilation of Air Pollutant Emission Factors* (1985b) (commonly referred to as AP-42) was used by both EPA and California to estimate air emissions due to wind erosion. EPA uses the Agency's Industrial Source Complex Short Term Model, Version 3 (ISCST3) to estimate air dispersion and deposition of windblown contaminants. California uses an air model developed by Hanna et. al. (1982) to estimate dispersion and deposition of particulates.

9.1.2 Differences in Key Modeling Parameters

9.1.2.1 <u>Plant Uptake Factors</u>. For the California study, distributions used to estimate plant uptake of metals are developed based on data obtained from the literature. Most of California's uptake factor data are from pot and greenhouse studies, but field measurements are also included. California uses uptake factors from studies involving nonorganic-based fertilizers and inorganic salts. Data from studies using sewage sludge application or plants grown in solution are specifically excluded from the California analysis.

The plant uptake factor distributions used by EPA are also developed based on data available in the literature. The Agency conducted a broad literature search in an effort to compile representative plant uptake data for agricultural soils. EPA considers all of the references cited in the California report as well as other sources not cited by California in deriving uptake distributions. Like California, EPA excludes data from studies conducted in a sewage sludge matrix. EPA also collected data from both field and greenhouse studies. Generally, there is more data available in the literature from greenhouse studies than from field studies. However, because greenhouse study data tend to show higher uptake rates than field study data and therefore may not accurately represent agricultural settings (Chaney and Ryan, 1994), using only field data to develop plant biouptake factors is generally recommended if possible. EPA conducted a sensitivity analysis to determine the effect of excluding greenhouse study data. (See Section 5 of this report for a detailed discussion of the sensitivity analysis.) Based on the results of the sensitivity analysis, EPA decided to exclude data from greenhouse studies and rely solely on field data for those compounds for which sufficient field data are available. For compounds for which sufficient field data are lacking, EPA supplements field data with data from greenhouse and pot studies. The compounds for which supplemental data are needed include nickel uptake into fruits, grains, and root crops; vanadium uptake into fruits, grains, herbage, and root crops; and zinc uptake into fruits. Details of the derivation of these factors are presented in Section 5.

Both California and EPA use plant biouptake distributions specific to each of the crop types assessed in their respective fertilizer analyses. Table 9-1 compares the plant uptake factors used in each analysis. No consistent trend or pattern is apparent in the comparison; the California values are higher in some cases while the EPA values are higher in others. The Br ranges for each metal-crop type combination are also larger in some cases for the California data and in other cases for the EPA data. The EPA data set tends to have a larger number of data points for each metal-crop type combination. The EPA data set also includes data for noncrop species as well as crop species; the California data are exclusively for edible crops. The EPA data and the California data both include some sites where the metals in soils are from sources other than fertilizer application (e.g., mine waste, urban/anthropogenic atmospheric deposition, news print, ash amendments). In general, both sets of uptake values tend to range over three or four orders of magnitude. Higher uptake factors imply that metals are more bioavailable and are taken up into plant tissue in proportionately greater amounts.

9.1.2.2 Soil-Water Distribution Coefficients (K_d). As discussed in Section 4, the K_d is used in evaluating metal mobility in the environment, and different methods are available to estimate the K_d. Table 9-2 presents a comparison of K_d values used in the California study to values used in the fertilizer risk assessment. The K_d values used in the California study are single values derived from Baes and Sharp (1983), which presents K_d values compiled for agricultural soil settings within a pH range of 4.5 to 9. The values used in EPA's fertilizer risk assessment represent a subset of data collected by EPA in 1998 (Allison, 1998). Data included in the Allison study are measured values reported in the scientific literature for soil-water systems. The data subset was culled using the same pH range defined by Baes and Sharp (1983). In compiling K_d values for use in its fertilizer risk assessment, EPA used only those references that provide K_d data on systems that closely approximate the conditions of agricultural soils.

K_d is influenced by multiple interrelated geochemical parameters including pH, soil type, and metal concentration. Consequently, K_ds are characterized by ranges that can span many orders of magnitude, depending on the metal and the system of interest. Table 9-2 presents K_d distributions for arsenic (V), cadmium, and lead as defined for the fertilizer risk assessment and the California study.

Table 9-1. Comparison of California and EPA Plant Uptake Factors

	Grains		Herbage	Vegetables	Roots	
Summary Statistics	**EPA**	**CDFA**	**EPA**	**CDFA**	**EPA**	**CDFA**
Lead						
Mean	1.092E-01	9.600E-03	1.228E-01	1.400E-02	4.639E-02	2.600E-02
Standard deviation	7.380E-02	9.590E+00	1.954E-01	5.800E+00	7.399E-02	4.320E+00
Minimum	6.957E-03	1.000E-04	5.217E-04	1.000E-04	6.452E-04	1.000E-03
Maximum	2.553E-01	1.830E-01	9.063E-01	3.900E-01	4.806E-01	8.300E-01
Number of data points	17	13	50	43	92	38
Arsenic						
Mean	4.955E-03	2.000E-02	6.533E-02	2.400E-02	9.855E-02	1.100E-02
Standard deviation	2.724E-03	2.660E+00	7.900E-02	3.890E+00	2.545E-01	4.090E+00
Minimum	6.667E-04	4.000E-03	1.000E-03	1.000E-03	8.980E-04	7.000E-04
Maximum	1.000E-02	6.000E-02	3.333E-01	3.570E-01	1.170E+00	1.010E-01
Number of data points	19	9	24	27	23	9
Cadmium						
Mean	5.042E-01	9.200E-02	8.113E-01	6.800E-01	7.477E-01	3.080E-01
Standard deviation	1.298E+00	7.110E+00	8.334E-01	4.440E+00	9.484E-01	5.020E+00
Minimum	2.500E-03	5.000E-04	2.500E-03	4.000E-03	1.250E-02	5.000E-03
Maximum	9.000E+00	2.500E+00	4.000E+00	1.330E+01	3.706E+00	5.700E+00
Number of data points	184	29	54	42	35	43

Table 9-2. Comparison of K_d Values

	Fertilizer Median L/kg	Fertilizer Minimum L/kg	Fertilizer Maximum L/kg	California Study L/kg
Arsenic (V)	2,520	2	20,400	6.69
Cadmium	864	1	100,000	6.69
Lead	21,000	5	100,000	99.48

The K_d values used in the California study are at the lower end of the range defined for the EPA fertilizer risk assessment. This may reflect bias resulting from the use of a limited number of data sources to define the Baes and Sharp (1983) distribution. Generally, at lower K_ds, cationic metals are more soluble in water and have greater availability for transport in the environment (i.e., low K_ds translate to higher metals concentration in the dissolved phase or soil pore water and lower metals concentration in the soil substrate). Consequently, at lower K_ds, higher concentrations of metal are leached to the groundwater. Alternatively, at higher K_ds, metals tend to bind to soils and are less likely to be leached.

9.1.3 California Risk-Based Concentrations

As discussed above, the results of California's assessment are presented as RBCs for lead, cadmium, and arsenic. The RBCs generated by the California assessment are shown in Table 9-3. EPA's risk assessment does not and was not designed to generate RBCs or standards for fertilizers, so the results of the two assessments cannot be directly compared. However, a discussion of how California's RBCs may be compared to Canada's fertilizer standards is presented in Section 9.4.

9.2 EPA Sewage Sludge Regulations

EPA's Standards for the Use or Disposal of Sewage Sludge (40 CFR Part 503) establish requirements for sewage sludge (or biosolids) applied to the land to condition the soil or fertilize crops or other vegetation. These regulations set limits on the amount of inorganic pollutants allowed in land-applied sewage sludge. The requirements of the Part 503 rule are based on the results of an extensive multimedia risk assessment. A comparison of pertinent aspects of the sewage sludge and fertilizer risk assessments is provided below.

9.2.1 Differences in Risk Methodology

In general, similar pathways and receptors are assessed for both EPA's sewage sludge and fertilizer analyses. The sewage sludge assessment uses a deterministic approach, whereas the fertilizer assessment uses a probabilistic methodology to estimate risk. However, because the Part 503 assessment is specific to sewage sludge and this assessment looks at fertilizers, all assumptions regarding the characterization of the materials (fertilizers versus sewage sludge) and their application differ significantly between the two assessments. And, because these two assessments analyze fundamentally different materials, they are not directly comparable in terms of methodology, input parameters, or results. At best, the following comparisons serve to illustrate significant differences between sewage sludge and fertilizer matrices.

9.2.2 Differences in Key Modeling Parameters

9.2.2.1 <u>Differences in Soil-Water Partition Coefficients (K_d)</u>. Table 9-4 presents a comparison of K_d values used in the sewage sludge study to values used in the fertilizer risk assessment. The K_d values used in the sewage sludge study were derived from Gerritse et al. (1982), which addresses the effect of sewage sludge on metal mobility in soils. As noted above,

Table 9-3. Unit Risk-Based Metal Concentrations in Fertilizers - Summary Table (10th Percentile[a])

	Receptor/Pathway(s)							
Chemical	**Farm Child Multi-Crop Exposure**	**Farm Child Vegetable Crop Exposure**	**Farm Child Root Crop Exposure**	**Farm Child Grain Crop Exposure**	**Farm Adult Multi-Crop Exposure**	**Farm Adult Vegetable Crop Exposure**	**Farm Adult Root Crop Exposure**	**Farm Adult Grain Crop Exposure**
Phosphates								
Arsenic	34	192	309	38	19	99	206	24
Cadmium	16	68	134	21	36	112	246	52
Lead	97	1,291	838	105	170	1,897	1,214	194
Micronutrients								
Arsenic	260	2,401	4,096	275	155	1,273	2,795	175
Cadmium	134	835	1,799	151	316	1,369	3,204	375
Lead	738	16,213	11,587	765	1,352	23,574	16,979	1,445

Note: Units are mg metal/kg nutrient (P_2O_5) or micronutrient-containing fertilizer.

[a] The values in this table represent the 10th percentile values of the unit RBC range generated for each receptor-pathway combination. This means these values are considered protective of the 90th percentile exposure estimate (90 percent of the modeled exposures) for each receptor, or that 90 percent of the farm family exposures modeled would be considered acceptable at these fertilizer metal concentrations, as modified to reflect the true percentage of nutrient in the fertilizer (i.e., the phosphate fertilizer 0-20-0 contains 20 percent P_2O_5, so 20 x the phosphate unit RBC = 0-20-0 RBC).

Example: The RBC for adult exposure to fertilizer arsenic via multi-crop exposures is 19 mg/kg. The 0-20-0 RBC would be 20 x 19 = 380 mg/arsenic/kg P_2O_5 fertilizer. **THESE RBCs ARE UNIT FACTORS AND ARE NOT INTENDED FOR DIRECT APPLICATION TO FERTILIZERS AS PRESENTED ABOVE. The reader is warned against using these RBCs without a complete understanding of how they are derived, the intended use of the RBCs, and how to derive RBCs for specific fertilizers. It is important to note that the RBCs presented above are tools, and fertilizers that have metal concentrations above these levels do not necessarily constitute a human health risk.**

Source: CDFA, 1998.

Table 9-4. Comparison of K_d Values

	Fertilizer Median L/kg	Fertilizer Minimum L/kg	Fertilizer Maximum L/kg	Sewage Sludge Study L/kg
Arsenic (V)	2,520	2	20,400	----
Arsenic	---	----	----	20
Cadmium	864	1	100,000	431
Chromium (III)	8,116	10	55,900	----
Chromium (VI)	13	0	1,800	----
Chromium	750	2	2,520	59
Copper	491	1	4,320	98
Lead	21,000	5	100,000	621
Mercury (II)	6,800	150	570,000	---
Mercury	---	----	----	330
Nickel	1,172	9	5,750	63

the systems defined for the sewage sludge study and the fertilizer risk assessment are dissimilar, and direct data comparisons are not appropriate.

9.2.2.2 <u>Differences in Soil-Plant Uptake Values</u>. Data used to calculate soil-plant uptake factors for the sewage sludge study are taken primarily from large-scale studies in which sewage sludge was applied to commercial fields. Biouptake factors derived from studies evaluating uptake in inorganic soil matrices (i.e., fertilizer-amended soils) are excluded from consideration for the Part 503 sludge analysis where possible. In a few instances, studies using application of metal salts are used if no other studies were available. Studies conducted in pot environments or under greenhouse conditions are also largely excluded from the sewage sludge analysis. In contrast, for the fertilizer assessment, studies conducted with a sewage sludge matrix are excluded from consideration in developing plant biouptake factors—only studies conducted in inorganic soil matrices are used to generate plant biouptake factors for the fertilizer study.

As discussed above, EPA conducted a sensitivity analysis to determine how use versus exclusion of greenhouse study data would potentially affect the results of the fertilizer analysis. (See Section 5 of this report for a detailed discussion of the sensitivity analysis.) As previously noted, use of greenhouse study data is generally not recommended because greenhouse study data tend to show higher uptake rates than field study data and so may not accurately represent agricultural settings (Chaney and Ryan, 1994). In addition, EPA's sensitivity analysis indicated that use of greenhouse data would tend to result in higher uptake values. Therefore, the Agency decided to rely exclusively on field study data where possible (i.e., for those compounds for which sufficient field data are available). For compounds for which sufficient field data are lacking, EPA supplements field data with data from greenhouse and pot studies. The compounds for which supplemental data are needed include nickel uptake into fruits, grains, and root crops; vanadium uptake into fruits, grains, herbage, and root crops; and zinc uptake into fruits.

Table 9-5 compares the uptake factors used in the fertilizer risk assessment with those used in the sewage sludge risk assessment. As expected, the uptake factors derived from data for soils amended with fertilizers are higher than the factors developed from sewage sludge data. As discussed above, metals are less bioavailable in soils amended with sewage sludge, and thus the uptake factors are lower. For this sewage sludge assessment, plant uptake slopes were developed for each of seven categories. The categories were chosen because they correspond to food categories used to estimate human dietary intake. Table 9-5 shows the seven categories used in the analysis.

9.2.3 Differences in Material Matrices

The differences in partitioning coefficients and plant uptake factors discussed above are due to the difference between sewage sludge and fertilizers in organic matter content and in chemical composition. In general, sewage sludge exhibits greater metal adsorption capacity than fertilizers, which results in increased metal adsorption in sludge-amended soils. Organic matter provides reactive sites that bind metals, thereby limiting metal mobility and making metals less bioavailable to plants. Biosolids are by definition rich in organic matter. Thus, sewage sludge tends to absorb or bind metals, thereby decreasing their availability for uptake by plants. Fertilizers, on the other hand, are composed primarily of inorganic salts and are essentially devoid of organic matter. Due to the absence of organic binding sites, metals applied as a component of organic salts or fertilizers tend to be more mobile and are more readily taken up by plants. In addition, the hydrous Fe, Mn, and Al oxides of biosolids provide increased metal adsorption ability to soils, while the fertilizer products usually have little effect on the metal absorption ability of the soil. Thus, as the organic portion of the sewage sludge decreases over time, the inorganic adsorption of metals increases. Studies conducted for the sewage sludge analysis (U.S. EPA, 1992) and other studies (Bechtel Jacobs, 1998; Chaney and Ryan, 1994) have demonstrated that metals are more available and are taken up by plants at a higher rate in soils not amended with sewage sludge. Plant uptake rates in sewage sludge-amended soils approach a plateau with increased rates of sludge application. In contrast, soils amended with metal salts show a linear increase in metal uptake with increased application of metal salts.

Consequently, the soil-plant uptake values and K_d values developed for the sewage sludge risk assessment are generally not applicable to the fertilizer study, and the metal loading rates and resultant exposure levels estimated for land application of sewage sludge are expected to be different. As a result, the pollutant loading limits and supporting data for sewage sludge are not directly applicable to risk associated with metals in fertilizers.

Table 9-5. Comparison of Sewage Sludge and Fertilizer Plant Uptake Factors

Br Values: Sewage Sludge vs. Fertilizers Comparison (field study data only for fertilizers)			
Arsenic			
Sewage Sludge Uptake Factor		**Fertilizer Mean Uptake Value**	
Grains/cereals	0.002	Grains	0.005
Potatoes	0.002	Roots	0.099
Root vegetables	0.004		
Leafy vegetables	0.018	Herbage	0.065
Legumes	0.001	Forage	0.472
Peanuts	0.001		
Garden fruits	0.001	Fruits	0.007
Cadmium			
Sewage Sludge Uptake Factor		**Fertilizer Mean Uptake Value**	
Grains/cereals	0.031	Grains	0.504
Potatoes	0.004	Roots	0.748
Root vegetables	0.032		
Leafy vegetables	0.182	Herbage	0.811
Legumes	0.002	Forage	0.922
Peanuts	0.002		
Garden fruits	0.045	Fruits	0.039
Mercury			
Sewage Sludge Uptake Factor		**Fertilizer Mean Uptake Value**	
Grains/cereals	0.043	Grains	0.568
Potatoes	0.001	Roots	0.036
Root vegetables	0.007		
Leafy vegetables	0.005	Herbage	0.518
Legumes	0.001	Forage	1.519
Peanuts	0.001		
Garden fruits	0.005	Fruits	3.931

Table 9-5. (continued)

Br Values: Sewage Sludge vs. Fertilizers Comparison (field study data only for fertilizers)

(continued)

Nickel

Sewage Sludge Uptake Factor		Fertilizer Mean Uptake Value	
Grains/cereals	0.003	Grains	n/d
Potatoes	0.005	Roots	n/d
Root vegetables	0.004		
Leafy vegetables	0.016	Herbage	0.009
Legumes	0.031	Forage	0.726
Peanuts	0.031		
Garden fruits	0.003	Fruits	n/d

Zinc

Sewage Sludge Uptake Factor		Fertilizer Mean Uptake Value	
Grains/cereals	0.027	Grains	0.97
Potatoes	0.012	Roots	0.135
Root vegetables	0.022		
Leafy vegetables	0.125	Herbage	0.774
Legumes	0.018	Forage	0.791
Peanuts	0.018		
Garden fruits	0.023	Fruits	n/d

9.2.4 Standards for Sewage Sludge Used Agriculturally

The sewage sludge assessment is used as a basis for setting maximum concentration limits for nine heavy metals. Annual pollutant loading limits for sewage sludge are provided in Table 9-6. Again, since the findings of EPA’s fertilizer assessment are not presented in terms of risk-based standards, the results of this study cannot be directly compared with those from the biosolids assessment. More importantly, due to the significant differences between sewage sludge and fertilizers outlined above, comparisons between sewage sludge standards and standards intended for fertilizers generally are unlikely to yield meaningful results.

9.3 Canadian Standards for Fertilizer and Soil Supplements

The Canadian Food Inspection Agency established metal standards for soil-applied fertilizers and supplement products. These standards are based on limits originally developed in 1978 as part of Ontario's provincial guidelines for land application of sewage sludge. The Ontario guidelines were reviewed by a team of experts on soils partitioning and soil-plant uptake characteristics and compared with national data on background soil metal concentrations. National standards similar to the Ontario standards were adopted for land application for sewage sludge in 1980. The national sewage sludge standards were re-evaluated in 1993 and a decision was made at that time to apply the same soil loading standards to all soil-applied fertilizers and supplements. Annual loading limits established by the Canadian standards are provided in Table 9-6.

It is important to note that the Canadian standards are not based on a quantitative assessment of risk but instead reflect the best professional judgment of a number of experts on metals behavior in soils and plants (Blair and Webster, 1997). The standards consist of both maximum annual loadings and maximum acceptable cumulative additions of metals applied as a component of fertilizers. Again, the standards are not risk-based and are, therefore, not supported by a quantitative analysis of biotransfer of metals through various media. Consequently, no supporting data or analyses are available for direct comparison with methodologies used in the other risk-based assessments discussed here.

9.4 Comparison of Standards

Both the Canadian and U.S. biosolids standards can be presented as cumulative/ maximum acceptable concentrations (i.e., the total amount of a metal that may be applied to the soil over a specified number of years) or as annual loading rates (i.e., the amount of a metal that may be applied annually). Table 9-6 provides a comparison between annual metals loading limits prescribed by the sewage sludge regulations and the Canadian standards for the same metals.

Table 9-6 also shows annual pollutant loading rates that are likely to result from proposed changes to the sewage sludge regulations likely to be proposed in the *Federal Register* (FR) later this year. EPA’s Office of Water (OW) is planning to propose that all sewage sludge be required to meet the existing pollutant concentrations for exceptional quality biosolids based on the assumption that biosolids are applied annually over a 100-year period. The OW is not planning on retaining annual pollutant loading rate limits in its proposed revisions to the Part 503 standards. However, annual pollutant loading rates can be calculated based on the pollutant limits for exceptional quality sludge and assumptions regarding the period of application. The calculated annual pollutant loading rates in Table 9-6 are derived loading rates for biosolids that meet the exceptional quality pollutant concentration limits, assuming that the sludge is applied annually for a period of 100 years.

Table 9-6. Comparison of Fertilizer Standards for Metals

Metal	Canadian Annual Loading Rate (kg/ha/yr)[a]	Current Sewage Sludge Annual Pollutant Loading Rates (kg/ha/yr)[b]	Calculated Annual Pollutant Loading Rates - Based on Expected Revisions to Part 503 Standards (kg/ha/yr)
As	0.33	2	0.41
Cd	0.09	1.9	0.39
Cr	NA	NA	NA
Cu	NA	75	15
Pb	2	15	3
Hg	0.02	0.85	0.17
Ni	0.8	21	4.2
Se	NA	5.0	1
Zn	8	140	28

[a] Fertilizer products are assumed to be applied annually at a rate of 4,400 kg per ha for 45 years. Limits are for products containing 5 percent nitrogen or less. Acceptable concentrations increase proportionally with total N concentrations above 5 percent.

[b] Sewage sludge is assumed to be applied annually by home gardeners for 20 years or semiannually for 40 years.

The results of the California risk assessment are reported in a format that is not directly comparable with the Canadian or sewage sludge standards. California's RBCs for phosphate-containing products are expressed on a per phosphate unit basis. Similarly, RBCs for micronutrients are expressed on a percent micronutrient basis (see Table 9-3).

California's RBCs may be converted to annual loading limits for different types of fertilizers or micronutrients by using (1) the appropriate RBCs combined with (2) corresponding assumptions regarding fertilizer composition (i.e., percent phosphorus) and/or micronutrient composition (e.g., percent zinc) and (3) corresponding assumptions regarding expected annual application rates. Table 9-7 shows calculated annual application rates for each metal and crop type. These application rates are calculated using the annual nutrient application rates used by California to generate RBCs and the most conservative RBCs derived for each compound (see Table 9-3).

Table 9-7. Calculated Application Rates for California Risk-Based Concentrations

Metal	Product Type	Application Rate[1] (kg/ha/yr)
Vegetables		
Pb	P_2O_5	0.654
	Micronutrients	0.494
As	P_2O_5	0.128
	Micronutrients	0.104
Cd	P_2O_5	0.108
	Micronutrients	0.090
Roots		
Pb	P_2O_5	0.720
	Micronutrients	0.494
As	P_2O_5	0.141
	Micronutrients	0.104
Cd	P_2O_5	0.119
	Micronutrients	0.090
Grains		
Pb	P_2O_5	0.407
	Micronutrients	0.494
As	P_2O_5	0.080
	Micronutrients	0.104
Cd	P_2O_5	0.067
	Micronutrients	0.090

[1] Application rates are calculated using nutrient requirements presented in the CDFA risk assessment document and the most conservative RBCs for each metal in phosphate fertilizers and in micronutrient products.

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Glossary

Air dispersion and deposition model – A model used to estimate the initial fate and transport of vapor and particle emissions in the environment conducted with the U.S. Environmental Protection Agency (EPA) Industrial Source Complex Short Term, Version 3 (ISCST3). ISCST3 is used to estimate air concentration of vapors, wet disposition of vapors, air concentration of particles, wet deposition of particles, and dry deposition of particles.

Air Pollution Emissions Factors (AP-42) – A series of equations used to estimate the rate of emission for particles under various conditions. In this analysis, the equations are used to estimate emission rates for annual average windblown emissions and for intermittent emissions due to fertilizer application and tilling operations.

Air dispersion model – A group of related mathematical algorithms used to estimate (model) the dispersion of pollutants in the atmosphere due to transport by mean (average) wind and small-scale turbulence.

Application rate – The amount of an applied substance measured as the mass per unit area.

Average daily dose – A measurement averaged over the exposure duration representing the estimated chronic daily intake of a noncarcinogenic substance.

Biosolid - Sewage sludge applied to the land to condition the soil or to fertilize crops or other vegetation. Because biosolids are rich in organic matter, sewage sludge tends to absorb or bind metals, thereby decreasing their availability for uptake by plants.

California risk-based concentration – California uses the mid-point of EPA's acceptable risk range to define unacceptable risk as "a theoretical upper-bound incremental cancer risk greater than 1×10^{-5} (one in 100,0000 and a theoretical non-cancer level greater than a hazard index (HI) of 1.0."

Canadian standards for fertilizer and soil supplements – Metal standards established for soil-applied fertilizer and supplemental products by the Canadian Food Inspection Agency. These standards are based on limits originally developed in 1978 as part of Ontario's guidelines for land application of sewage sludge. The standards were re-evaluated in 1993.

Cancer slope factor (CSF) – The cancer risk (proportion affected) per unit of dose. The slope factor can be used to compare the relative potency of different chemical substances on the basis either of chemical weight or moles of chemical.

Carcinogenic – A substance known to cause cancer.

Cement kiln dust (CKD) – A by-product from the manufacture of cement. Contains 4 percent to 12.8 percent potash (K_2O) and averages 30 percent calcium. An excellent liming material. High content of calcium oxide produces equilibrium pH in suspension of about 12.

Climate parameters – Information about the climate, including annual rainfall and annual average wind speed. This information is obtained from existing geographic information system (GIS) databases.

Contaminant – A constituent or component of a fertilizer that is not part of the guaranteed analysis and/or (1) is not a macronutrient (primary or secondary), (2) is not a micronutrient, (3) is not required for plant nutrition (e.g., cadmium, lead, arsenic, mercury, radionuclides, dioxins), and (4) may be essential for some plants (and humans) at low levels or in one oxidation state but toxic at higher levels or in a different oxidation state (e.g., chromium, nickel, vanadium, copper, zinc). Contaminant constituents are present naturally in inorganic fertilizer ores and in industrial by-products reprocessed for fertilizers.

Crop yield for forage – A measure estimated as a weighted average of crop yields for pasture grass and hay.

Dioxins – Unintended by-products formed during the combustion of organic compounds in the presence of chloride. The production of certain chlorinated organic products also produces dioxins as contaminants, as does chlorine bleaching of wood pulp. Dioxins have no commercial or domestic applications and are not intentionally produced, except in small quantities for research.

Distribution coefficient (K_d) – A coefficient that describes contaminant partitioning between solid and aqueous phases. Commonly used in environmental studies to assess the fate and mobility of contaminants in different environmental settings (e.g., agricultural soil environments). The distribution coefficient is contaminant-specific as well as system-specific and is calculated as the concentration of contaminant sorbed to the substrate divided by the concentration of contaminant present in the liquid phase.

Dry weight (dw) – The total weight after removal of the water content.

Emissions – Substances discharged into the air.

Erosion – Soil loss by the actions of water or wind.

Exposure point concentration – The concentration of a chemical in its transport or carrier medium at the point of contact.

Exposure pathway – The course a chemical or physical agent takes from a source to an exposed organism. An exposure pathway describes a unique mechanism by which an individual or population is exposed to chemicals or physical agents at or originating from a site. Each exposure pathway includes a source or release from a source, an exposure point, and an exposure route. If the exposure point differs from the source, a transport/exposure medium (e.g., air) or media (in cases of intermedia transfer) also would be indicated.

Exposure parameters – Such variables as ingestion rates, exposure frequencies, and human body weights used to calculate daily doses (or intake levels) for individual receptors.

Fate and transport modeling – A set of related mathematical algorithms used to predict or estimate the disposition of a chemical in various media or locations as a result of transport, partitioning, uptake, and degradation.

Fertilizer – A substance that contains one or more recognized plant nutrients that is specially designed to be used for its plant-nutrient content and is claimed to promote plant growth. A fertilizer material is a fertilizer that (1) contains important quantities of no more than one of the primary plant nutrients: nitrogen (N), phosphorus (P), and potassium (K); (2) has 85 percent or more of its plant-nutrient content present in the form of a single chemical compound; or (3) is derived from plant or animal residue, by-products, or natural material deposits that have been processed in such a way that their content of plant nutrients has not been materially changed except by purification and concentration.

Fertilizer consumption – Use of commercial fertilizers for agricultural purposes.

Filler – A substance added to fertilizer materials to provide bulk, prevent caking, or serve some purpose other than providing essential plant nutrients.

Food chain – A chain of organisms existing in any natural community such that each link in the chain feeds on the one below it and is eaten by the one above, with autotrophs on the bottom and the largest carnivores at the top.

Geographic Information Retrieval and Analysis System (GIRAS) – A system used to identify geographic areas that are used for agriculture. GIRAS provides comprehensive land use data in digital GIS format.

Guaranteed analysis – The minimum percentage of plant nutrients claimed in a fertilizer that is found on the fertilizer's label.

Gypsum – A product consisting chiefly of calcium sulfate with combined water ($CaSO_4 \bullet 2H_2O$) incapable of neutralizing soil acidity. Occurs in large deposits of soft crystalline rock and as sand. A granulated form has been developed for application to soil (for growing peanuts and other crops) as a calcium source or sulfur source either by itself or in a blend of other fertilizers. In irrigated agriculture, it is used to increase permeability of soils.

Hazard index (HI) – The sum of two or more hazard quotients for multiple substances and/or multiple exposure pathways.

Hazard quotient (HQ) – The ratio of a single substance exposure level over a specified time period to a reference dose for that substance derived from a similar exposure period.

Heavy metals – Certain metals, such as arsenic, cadmium, lead, mercury, and nickel, that may be present in varying concentrations in naturally occurring ores or in industrial by-products that contain plant nutrients and are processed for fertilizers.

Incidental ingestion – Unintentional ingestion that occurs accidentally or unknowingly.

Indirect exposure model (IEM) – A method used to estimate exposure point concentrations and individual risk by indirect or food chain pathways.

Indirect exposure model – A method of estimating the fate and transport of constituents through the environment and into the food chain to produce estimates of the human health risk.

Industrial by-product – Waste material from various industrial processes that contains plant nutrients. These products may be converted into fertilizer materials, depending upon their physical condition and their content of possibly undesirable contaminants.

Ingestion – Exposure through eating or drinking.

Integrated Exposure Uptake Biokinetic (IEUBK) Model – A model for lead that calculates blood lead level concentrations. To estimate blood lead levels, exposure point concentrations of lead are used as inputs.

Interception fraction (Rp) – A fraction calculated from crop yield and, according to EPA, “accounts for the fact that not all of the airborne material depositing within a unit area will initially deposit on edible vegetation surfaces.”

Key meteorologic data for the ISCST3 model – A group of four key factors: (1) the wind direction, which determines the direction of the greatest impacts; (2) the windspeed (the ground-level air concentration is inversely proportional to the windspeed, so the lower the windspeed, the higher the concentration); (3) the stability class, which has an impact on the rate of lateral and vertical diffusion (the more unstable the air, the greater the diffusion); and (4) the mixing height, which indicates the height to which pollutants can be diffused vertically.

Lifetime average daily dose – A measurement averaged over an individual’s lifetime representing the estimated chronic daily intake of a carcinogenic substance.

Lime (liming material) – A product whose calcium and magnesium compounds are capable of neutralizing soil acidity.

Liming agent – A product intended to neutralize soil acidity. Liming agents have moderate concentrations of metals but very high application rates.

Macronutrients – A nutrient that plants require for growth in relatively large amounts. Macronutrients include both primary and secondary nutrients.

Meteorological regions – The 29 representative regions developed under the EPA's Superfund soil screening levels program. Regions were defined based on data from 200 meteorologic stations across the U.S. and are considered representative of meteorologic conditions in the continental U.S.

Micronutrients – A nutrient essential for the normal growth of plants that is required in relatively small amounts. Micronutrients include boron, chlorine, cobalt, copper, iron, manganese, molybdenum, sodium, and zinc.

National Food Consumption Survey (NFCS) – A survey conducted every 10 years to analyze the food consumption behavior and dietary status of Americans.

Nitrogen (N) – An essential element for plant growth. Not used as a fertilizer per se, but the chemical term used for the basic measure of the nitrogen content in diverse fertilizers such as nitrates, ammonium slats, liquid ammonium, urea, and natural organics.

Organic fertilizer – A material that contains carbon and one or more elements in addition to hydrogen and oxygen that are required for plant growth.

Phosphorus oxide (P_2O_5) – Not used as a fertilizer per se, but the chemical term used for the basic measure of the phosphorus (P) content in diverse phosphate fertilizers such as calcium phosphates, ammonium phosphates, polyphosphates, and superphosphates.

Pica – A craving for unnatural foods, such as chalk, dirt, and ashes.

Plant uptake factor – A factor estimating the proportion of a constituent in the growing medium that is taken into plants via the plant's physiological mechanisms.

Polychlorinated dibenzofurans (PCDFs) – Persistent environmental pollutants that accumulate, primarily through food chains, in the tissues of animals, including humans. Exposures to PCDFs are associated with enzyme induction, chloracne, immunotoxicity, developmental toxicity, and cancer in both animals and humans.

Polychlorinated dibenzo-*p*-dioxins (PCDDs) – Persistent environmental pollutants that accumulate, primarily through food chains, in the tissues of animals, including humans. Exposures to PCDDs are associated with enzyme induction, chloracne, immunotoxicity, developmental toxicity, and cancer in both animals and humans.

Pot studies – Studies of plant uptake rates that are performed by growing plants in pots rather than in the field. Plant uptake rates are generally higher under greenhouse conditions due to higher transpiration rates in relatively warm, humid greenhouse conditions.

Potash or potassium oxide (K_2O) – Not used as a fertilizer per se, but the chemical term used for the basic measure of the potassium (K) content in diverse potassium fertilizers such as potassium chloride, potassium sulfate, potassium nitrate, and potassium thiosulfate.

Primary nutrients – Nitrogen, phosphorus, and potassium.

Reference dose (RfD) – An estimate (with uncertainty spanning perhaps an order of magnitude) of a daily exposure to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime. The RfD is useful as a reference point from which to gauge the potential effects of the chemical at other doses.

Risk assessment – Determination of the kind and degree of hazard posed by an agent, the extent to which a particular group of people has been or may be exposed to the agent, and the present or potential health risk that exists due to the agent.

Risk-based concentration (RBC) – The amount (or concentration) of a substance (e.g., arsenic, cadmium, or lead) that can be present in commercially available inorganic fertilizers below which no theoretical upper-bound unacceptable risks to human health are posed.

Secondary nutrients – Calcium, magnesium, and sulfur.

Secondary fertilizers – Sulfur, liming materials, and gypsum products.

Soil partitioning – A method used to estimate the contaminant concentrations in soil after loss from soils as a result of degradation, volatilization, leaching, and rainwater runoff.

Soil amendment – Any substance added to soil (other than the substances used primarily as fertilizers) that is thought to improve the physical characteristics of the soil, such as porosity to water and air. Soil amendments do not include commercial fertilizers, agricultural liming materials, unmanipulated animal manures, unmanipulated vegetable manures, pesticides, and other materials exempted by regulation but can contain important fertilizer elements.

Soil-water partition coefficient (K_d) – See distribution coefficient.

TCDD – Tetrachlorinated dibenzo-*p*-dioxin, a dioxin congener.

Toxicity – (1) The harmful effects produced by exposure of an organism to a chemical. (2) The property of a chemical that causes harmful effects to organisms.

Toxicity equivalency factor (TEF) – A factor used to express the toxicity relationships among a family of structurally related chemical compounds. A factor used to estimate the health benchmark for the congener with respect to the toxicity of TCDD.

Toxicity equivalent quotient (TEQ) – The sum of all the toxicity equivalency factors (TEFs).

Uncertainty factor (Uf) – A factor applied to an exposure or effects concentration or dose to correct for identified sources of uncertainty.

Uncertainty – A factor inherent in the risk assessment process. Uncertainty occurs because the risk assessment process is complex, and variability is inherent in the environment.

Universal soil loss equation (USLE) – An equation to estimate soil erosion and overland transport of sediment from agricultural fields across intervening areas to nearby waterbodies using a distance-based sediment delivery ratio.

Wet weight (ww) – Weight in live or field conditions, before removal of the water content.