
APPENDIX G

Background Discussion for Soil-Plant-Human Exposure Pathway

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Introduction

The U.S. Environmental Protection Agency (EPA) has identified the consumption of garden fruits and vegetables as a likely exposure pathway to contaminants in residential soils. To address this pathway within the guidance, the Office of Emergency and Remedial Response (OERR) evaluated methods to calculate soil screening levels (SSLs) for the soil-plant-human exposure pathway. In particular, OERR evaluated algorithms and approaches proposed by other EPA offices or identified in the open literature. Key sources of information included the *Technical Support Document for Land Application of Sewage Sludge* (U.S. EPA, 1992), *Estimating Exposure to Dioxin-like Compounds* (U.S. EPA, 1994), *Plant Contamination* (Trapp and McFarlane, 1995), *Current Studies on Human Exposure to Chemicals with Emphasis on the Plant Route* (Paterson and Mackay, 1991), *Uptake of Organic Contaminants by Plants* (McFarlane, 1991), and *Air-to-Leaf Transfer of Organic Vapors to Plants* (Bacci and Calamari, 1991).

Although empirical data on plant uptake from soil (either through root or leaf transfer) are limited, a comprehensive collection of available empirical data on plant uptake is presented in the *Technical Support Document for the Land Application of Sewage Sludge* (U.S. EPA, 1992), hereafter referred to as the “Sludge Rule.” The Sludge Rule presents uptake-response slopes, or bioconcentration factors, for a number of heavy metals found in sewage sludge, including six metals addressed in the *Soil Screening Guidance* (i.e., arsenic, cadmium, mercury, nickel, selenium, and zinc). These empirical bioconcentration factors were used in the development of the generic plant SSLs presented in this appendix.

The Sludge Rule does not present uptake-response slopes for organic chemicals because of a lack of empirical data. Therefore, generic plant SSLs for organic contaminants are not presented in this appendix. Currently, EPA is evaluating mathematical constructs to estimate plant uptake of organic chemicals for several initiatives (e.g., Hazardous Waste Identification Rule, Office of Solid Waste; Indirect Exposure to Combustion Emissions, Office of Research and Development). In addition, new mathematical models are becoming available that use a fugacity-based approach to estimate plant uptake of organic compounds (e.g., PLANTX, Trapp and McFarlane, 1995). Once these methods are reviewed and finalized, OERR may be able to address the soil-plant-human exposure pathway for organic contaminants.

The methods and data used to calculate the generic plant SSLs for arsenic, cadmium, mercury, nickel, selenium, and zinc are presented below. For comparative purposes, data on the potential phytotoxicity of metals have also been included. In addition, the site-specific factors that influence the bioavailability and uptake of metals by plants are discussed. The potentially significant effect of these site-specific factors on plant uptake underscores the need for site-specific assessments where the soil-plant-human pathway may be of concern.

G.1 SSL Calculations from Empirical Data

For uptake of chemicals into edible plants, EPA recommends a simple equation to determine SSLs for the soil-plant-human exposure pathway. The equation is appropriate for both belowground and

aboveground vegetation, provided that the appropriate bioconcentration factor (Br) is used (see Section G.4). The screening level equation for the soil-plant-human pathway is given by:

SSL equation for the Soil-Plant-Human Pathway

$$\text{Screening Level (mg/kg)} = \frac{C_{\text{plant}}}{\text{Br}} \quad (\text{G-1})$$

Parameter/Definition (units)	Default
C_{plant} /acceptable plant concentration (mg/kg DW)	see Section G.2
Br/plant-soil bioconcentration factor (mg contaminant/kg plant tissue DW)/(mg contaminant/kg soil) ⁻¹	chemical- and plant-specific (see Section G.2)

It is important to note that the plant concentration is in dry weight (DW) instead of fresh weight (FW). Consequently, the consumption rates for plants must also be given in dry weight. For convenience, Table G-1 presents conversion factors with which to convert fresh weight to dry weight for a variety of garden fruits and vegetables. For example, because the conversion factor for lettuce is 0.052, 10 kg of lettuce fresh weight is equivalent to 0.52 kg of lettuce dry weight.

Several inputs to Equation G-1 are either derived from other equations or identified from empirical studies in the literature. Specifically, the derivation and data sources for C_{plant} and Br are discussed below.

G.2 Acceptable Concentration in Plant Tissue (C_{plant})

The acceptable contaminant concentration in plant tissues (C_{plant}) in mg/kg DW for fruits and vegetables is backcalculated using the following equation:

Acceptable Plant Concentration for Fruits and Vegetables (C_{plant})

$$C_{\text{plant}} = \frac{I \times \text{BW}}{F \times \text{CR}} \quad (\text{G-2})$$

Parameter/Definition (units)	Default
I/acceptable daily intake of contaminant (mg/kg-d)	see Section G.3
BW/body weight (kg)	70
F/fraction of fruits and vegetables consumed that are contaminated (unitless)	0.4 (see Section G.4)
CR/consumption rate for fruits and vegetables (kg-plant DW-d)	0.0197 (aboveground) 0.0024 (belowground) (see Section G.4)

Table G-1. Fresh-to-Dry Conversion Factors for Fruits and Aboveground Vegetables

Vegetables		Fruits	
Asparagus	0.070	Apple	0.159
Snap beans	0.111	Bushberry	0.151
Cucumber	0.039	Cherry	0.170
Eggplant	0.073	Grape	0.181
Sweet pepper	0.074	Peach	0.131
Squash	0.082	Pear	0.173
Tomato	0.059	Strawberry	0.101
Broccoli	0.101	Plum/prune	0.540
Brussels sprouts	0.151		
Cabbage	0.076		
Cauliflower	0.083		
Celery	0.063		
Escarole	0.134		
Green onions	0.124		
Lettuce	0.052		
Spinach green	0.073		
Average for vegetables	0.085	Average for fruits ^a	0.15

^a Plum/prune was omitted from the average as an outlier.

Source: Baes et al. (1984).

G.3 Acceptable Daily Intake (I) of Contaminants

For carcinogens, the acceptable daily intake (I) in mg/kg-day is calculated at the target risk level, using default assumptions for exposure duration, exposure frequency, and averaging time. At the target risk level, the acceptable daily intake of carcinogens may be calculated as follows:

Acceptable daily intake for carcinogens

$$I = \frac{TR \times AT \times 365 \text{ d/yr}}{ED \times EF \times CSF_{\text{oral}}} \quad (\text{G-3})$$

Parameter/Definition (units)	Default
TR/target risk level (unitless)	10 ⁻⁶
AT/averaging time (years)	70
ED/exposure duration (years)	30
EF/exposure frequency (d/yr)	350
CSF _{oral} /oral cancer slope factor (mg/kg-d) ⁻¹	chemical-specific (see Part 2, Table 1)

For noncarcinogens, the acceptable daily intake (I) in mg/kg-day is calculated at a hazard quotient of 1 using the following equation:

Acceptable daily intake (I) for noncarcinogens

$$I = \frac{HQ \times RfD \times AT \times 365 \text{ d/yr}}{ED \times EF} \quad (\text{G-4})$$

Parameter/Definition (units)	Default
HQ/target hazard quotient (unitless)	1
AT/averaging time (years)	30
ED/exposure duration (years)	30
EF/exposure frequency (d/yr)	350
RfD/oral reference dose (mg/kg-d)	chemical-specific (see Part 2, Table 1)

G.4 Contaminated Fraction (F) and Consumption Rate (CR)

Default values for the fraction of vegetables assumed to be contaminated (F) are recommended in the *Exposure Factors Handbook* (U.S. EPA, 1990). For home gardeners, a high-end dietary fraction of 0.40 is assumed for the ingestion of contaminated fruits and vegetables grown onsite.

The default values for total fruit and vegetable consumption rates (CR) cited in the *Exposure Factors Handbook* are 0.140 and 0.2 kg/d fresh weight, respectively. Assuming that the homegrown fraction is roughly 0.25 to 0.40, EPA estimated fresh weight consumption rates of: (1) 0.088 kg/d of aboveground unprotected fruits, (2) 0.076 kg/d of aboveground unprotected vegetables, and (3) 0.028 kg/d of unprotected belowground vegetables (U.S. EPA, 1994). The consumption rates for fruits and vegetables are converted to dry weight based on the average fresh-to-dry conversion of 0.15 for fruits and 0.085 for vegetables presented in Table G-1. For unprotected belowground vegetables, the consumption rate (CR) is calculated by multiplying the fresh weight consumption rate (0.028 kg FW/d) by the average conversion factor of 0.085 resulting in a CR of 0.0024 kg DW/d. Using this same method, dry weight consumption rates of 0.0132 and 0.0065 kg DW/d were calculated for unprotected aboveground fruits and vegetables, respectively. Consequently, the overall consumption rate (CR) for aboveground, unprotected fruits and vegetables is 0.0197 kg DW/d.

The distinction between protected and unprotected produce reflects evidence that, for protected plants such as cantaloupe and citrus, there is very little translocation of contaminants to the edible parts of the plant. EPA recognizes that, while these assumptions for contaminated fraction and consumption rates are reasonable for general assessment purposes, there is likely to be wide variability on the types of produce grown at home, the percentage that is unprotected, and other exposure-related characteristics (U.S. EPA, 1994).

G.5 Soil-to-Plant Bioconcentration Factors (Br)

For metals, soil-to-plant bioconcentration factors (Br) for both aboveground and belowground plants must be identified from empirical studies because the relationship between soil concentration and plant concentration has not been described adequately to provide a mathematical construct for

modeling. Table G-2 provides empirical plant uptake values for six metals identified in the *Technical Support Document for Land Application of Sewage Sludge* (U.S. EPA, 1992). Because of the variability in site-specific assessments, bioconcentration factors that are appropriate for the type of produce considered in a particular risk assessment should be selected. For general screening purposes, the geometric mean Br values for leafy vegetables and root vegetables are typically selected to represent aboveground and belowground plants, respectively. These values may be used to calculate SSLs for six metals for the soil-plant-human exposure pathway.

G.6 Example Calculation of Soil-Plant-Human SSL: Cadmium

To demonstrate how the methods described in this appendix may be used to calculate an SSL for the soil-plant-human pathway, a sample calculation is provide below for cadmium. Cadmium is considered a noncarcinogen via oral exposure and, therefore, the acceptable daily intake (I) is calculated using Equation G-4. Using the RfD for cadmium ingested in food of 1.0×10^{-3} mg/kg (the RfD is 5.0×10^{-4} in water), Equation G-4 may be solved for acceptable daily intake (I) of cadmium from a dietary source:

$$I = \frac{HQ \times RfD \times AT \times 365 \text{ d/yr}}{ED \times EF}$$

$$I = \frac{1 \times 1.0 \times 10^{-3} \text{ mg/kg-d} \times 30 \text{ yr} \times 365 \text{ d/yr}}{30 \text{ yrs} \times 350 \text{ d/yr}}$$

$$I = 1.0 \times 10^{-3} \text{ mg/kg-d}$$

The acceptable daily intake (I) is used in Equation G-2 to estimate the acceptable contaminant concentration in plant tissue (C_{plant}). However, Equation G-2 is designed to solve for the acceptable plant concentration (C_{plant}) in *either* aboveground fruits and vegetables or belowground vegetables. Consequently, Equations G-1 and G-2 must be combined to calculate the screening level for the ingestion of both aboveground and belowground produce. These equations are combined by summing the product of the category-specific produce intake and bioconcentration factors. Since the default contaminated fraction applies to both categories of produce, Equations G-1 and G-2 are combined to solve for the soil screening level:

$$\text{Screening Level (mg / kg)} = \frac{I \times BW}{F \times \sum (CR \times Br)} \quad (\text{G-5})$$

Table G-2. Summary Table of Empirical Bioconcentration Factors for Metals
(in mg contaminant per kg plant DW / mg contaminant per kg soil)

	Study observations	pH Range	Bioconcentration factors (Br)		Geometric Mean Br
			Min	Max	
Arsenic					
grains and cereals	1	7.5	0.026	0.026	0.026
potatoes	8	5.5 - 7.5	0.002	0.24	0.004
leafy vegetables	7	5.5 - 7.5	0.002	0.068	0.036
legumes	7	NR - 7.5	0.002	0.004	0.002
root vegetables	7	NR - 7.5	0.002	0.28	0.008
garden fruits	5	NR - 7.5	0.002	0.006	0.002
sweet corn	3	NR	0.002	0.002	0.002
Cadmium					
grains and cereals	14	4.4 - 8.0	0.002	0.346	0.36
potatoes	14	4.7- 8.0	0.002	0.076	0.008
leafy vegetables	71	4.6 - 8.4	0.002	14.12	0.364
legumes	14	5.1 - 7.7	0.002	0.054	0.004
root vegetables	25	4.6- 8.0	0.002	1.188	0.064
garden fruits	19	4.6 - 7.1	0.002	1.272	0.09
sweet corn	12	5.1 - 7.1	0.02	0.666	0.118
Mercury					
grains and cereals	1	5.3 - 7.1	0.0854	0.0854	0.0854
potatoes	1	5.3 - 7.1	0.002	0.002	0.002
leafy vegetables	9	5.3 - 7.1	0.002	0.092	0.008
legumes	3	5.3 - 7.1	0.002	0.002	0.002
root vegetables	6	5.3 - 7.1	0.002	0.086	0.014
garden fruits	7	5.3 - 7.1	0.002	0.086	0.01
sweet corn	default	ND	0.002	0.002	0.002
Nickel					
grains and cereals	10	6.2 - 8.0	0.002	0.11	0.01
potatoes	14	6.4 - 8.0	0.002	0.06	0.01
leafy vegetables	56	5.3 - 8.0	0.002	30	0.032
legumes	11	5.9 - 7.7	0.002	1.004	0.062
root vegetables	25	5.9 - 8.0	0.002	0.232	0.008
garden fruits	14	5.9 - 7.3	0.002	0.19	0.006
sweet corn	4	5.9 - 7.1	0.002	0.002	0.002
Selenium					
grains and cereals	4	5.5 - 7.0	0.002	0.11	0.002
potatoes	2	5.5 - 6.8	0.018	0.096	0.042
leafy vegetables	7	5.5 - 7.8	0.002	0.076	0.016
legumes	4	5.5 - 6.8	0.024	0.11	0.024
root vegetables	8	5.5 - 7.6	0.004	0.096	0.022
garden fruits	8	5.5 - 6.8	0.008	0.078	0.02
sweet corn	default	ND	0.002	0.002	0.002

Table G-2. (continued)

	Study observations	pH Range	Bioconcentration factors (Br)		Geometric Mean Br
			Min	Max	
Zinc					
grains and cereals	13	5.3 - 8.0	0.016	0.368	0.1
potatoes	14	4.7 - 8.0	0.01	0.122	0.024
leafy vegetables	47	4.6 - 8.0	0.012	4.488	0.25
legumes	10	5.1 - 7.7	0.002	0.11	0.036
root vegetables	20	4.6 - 8.0	0.002	0.412	0.044
garden fruits	21	4.6 - 7.3	0.002	0.394	0.046
sweet corn	8	5.1 - 6.5	0.002	0.19	0.02

NR = Not reported

ND = No data

The input parameters in Equation G-5 correspond to input parameters in Equations G-1 and G-2, with a contaminated fraction (F) of 0.4, and consumption rates (CR_{ag} and CR_{bg}) and bioconcentration factors (Br_{ag} and Br_{bg}) specific to either aboveground or belowground produce. Solving Equation G-5 for cadmium using the default parameters in Equation G-2 for F, CR_{ag}, and CR_{bg} results in:

$$\text{Screening Level} = \frac{I \times BW}{0.4 \times \Sigma(CR_{ag} \times Br_{ag}) + (CR_{bg} \times Br_{bg})}$$

$$\text{Screening Level} = \frac{1.0 \times 10^{-3} \text{ mg/kg-d} \times 70 \text{ kg}}{0.4 \times \Sigma(0.0197 \times 0.364) + (0.0024 \times 0.064) \text{ kg soil/d}}$$

$$\text{Screening Level} = 24 \text{ mg/kg soil}$$

As described above, the geometric mean Br values for leafy vegetables and root vegetables were selected to represent the bioconcentration factors (Br) for aboveground fruits and vegetables (Br_{ag}) and belowground vegetables (Br_{bg}), respectively (see Table G-2). SSLs for the plant pathway that are calculated using the bioconcentration factors for leafy and root vegetables are considered to be generic SSLs by OERR. During site-specific assessments, OERR recommends that a weighted average bioconcentration factor be used to reflect the type of produce grown and eaten locally.

G.7 Generic SSLs for Selected Metals

Table G-3 presents the generic SSLs for the soil-plant-human exposure pathway along with the SSLs for direct soil ingestion. In addition, this table presents plant toxicity values identified in the *Toxicological Benchmarks for Screening Potential Contaminants of Concern for Effects on Terrestrial Plants: 1994 Revision* (Will and Suter, 1994). The phytotoxicity values are either: (1) the

estimated 90th percentile of lowest observed effects concentrations (LOECs) from a data set consisting of 10 or more values, or (2) the lowest LOEC from a data set with less than 10 values. The toxicological endpoints for the phytotoxicity were limited to growth and yield parameters because they are the most common endpoints reported in phytotoxicity studies and are ecologically significant in terms of plant populations.

Table G-3. Comparison of Generic SSLs for Plant Pathway with the SSLs for Soil Ingestion and LOEC Values for Phytotoxicity (all values in mg/kg)

	Arsenic	Cadmium	Mercury	Nickel	Selenium	Zinc
Generic plant SSL	0.4	24	270	5400	2400	10000
Soil ingestion SSL	0.4	78	23	1600	390	23000
Migration to ground water SSL^a	29(1)	8(0.4)	2(0.1)	130(7)	5(0.3)	12000(620)
Phytotoxicity LOEC	10	3	0.3	30	1	50

^a Values based on DAF of 20 (DAF of 1).

The comparison of the generic SSLs for the plant pathway with SSLs for soil ingestion and migration to ground water suggests that this pathway may be of concern at sites contaminated with arsenic or cadmium. For mercury, nickel, and selenium, the generic plant SSLs are well above the SSLs based on soil ingestion and migration to ground water. Thus, although SSLs based on these other pathways are likely to be protective of the soil-plant-human pathway, other data suggest that phytotoxicity is likely to be the factor limiting exposure through plant uptake for these metals.

Phytotoxicity - The data in Table G-3 suggest that, for cadmium, mercury, nickel, and selenium, toxicity to plants will be observed at levels well below those estimated to elicit adverse effects in humans. The phytotoxicity of arsenic, nickel, and zinc have been well documented. However, despite the low phytotoxicity value for selenium, some authors have demonstrated that selenium can accumulate in certain plants at high levels (Bitton et al., 1980). Moreover, many phytotoxicity values are based on a reduction in yield that may result in higher levels in the surviving produce. Thus, with the exception of zinc, phytotoxicity should not be used to rule out this exposure pathway unless empirical data are available that are relevant to the site conditions (e.g., similar pH, organic matter) and the type of crops likely to be grown.

Soil Characteristics - Because the majority of the plant uptake data for metals were generated in sludge application studies, the empirical bioconcentration factors listed in Table G-2 may not be appropriate for use at all sites. For example, the adsorption "power" of sludge in the presence of phosphates, manganese, hydrous oxides of iron, and Ca^{+2} may reduce the amount of metal that is bioavailable to plants. In addition, soil pH strongly influences the ability of plants to absorb metals from soil. Several studies document that, as pH decreases, the bioavailability of many metals increases. In fact, agricultural practices maintain a soil pH of 5.5 or greater to protect against aluminum and manganese phytotoxicity. However, 40 percent of the data evaluated for the Sludge Rule were from studies in which the pH was less than 6, and, as a result, bioconcentration factors may be artificially skewed.

Chemical Characteristics - Another factor that heavily influences plant uptake of metals is the chemical form of the metal. Researchers have observed that plant uptake rates of metal salts in sludge tend to be higher than plant uptake rates in studies on elemental metals. Metal salts do not

adsorb to sludge the same way as “metals in nonsalt forms” and, consequently, they are more bioavailable to plants.

Type of produce - The bioconcentration potential of metals varies with plant type. As shown in Table G-2, the range of bioconcentration factors covers an order of magnitude for most metals across the seven categories of produce. Certain types of plants are resistant to some metals while these same metals may be highly toxic to other plant species. Depending on the type of crops grown, the generic soil-plant-human SSLs may not reflect the most appropriate measures of bioconcentration.

Dietary habits - The dietary habits of the home gardener may result in an increase or decrease in exposure. The default values for consumption rate (CR) and contaminated fraction (F) represent reasonably conservative estimates for these exposure parameters. However, individual consumers may ingest significantly different quantities of produce and, depending on their fruit/vegetable preferences, may rely on crops that are efficient accumulators of metals.

G.8 SSL Calculations for Organics Lacking Empirical Data

The lack of plant bioconcentration data on organics presented in the *Technical Support Document for Land Application of Sewage Sludge* (U.S. EPA, 1992) has been discussed in several other sources. For example, the status of empirical data on plant uptake and accumulation of organics was recently evaluated for a database on uptake/accumulation, translocation, adhesion, and biotransformation of chemicals in plants (Nellessen and Fletcher, 1993). This database, referred to as UTAB, is one of the most comprehensive data sources available on chemical processes in plants and contains over 42,000 records taken from more than 2,100 published papers. The authors found that, with the exception of pesticides, uptake-response data for organic chemicals are available for roughly 25 percent of the chemicals monitored by EPA. Given the comprehensive nature of the UTAB database, modeling may be the only alternative to evaluating the soil-plant-human pathway in the near future for many organic chemicals.

Recently, several authors have developed models to predict the uptake and accumulation of organic chemicals in plants (e.g., Matthies and Behrendt, 1994; McKone, 1994; Trapp et al., 1994). One of the most promising models for use as a risk assessment tool is PLANTX, a peer-reviewed partitioning model that describes the dynamic uptake from soil, or solution, and the metabolism and accumulation of xenobiotic chemicals in roots, stems, leaves, and fruits (Trapp et al., 1994). Unlike a number of other models used to estimate plant uptake, PLANTX is not based on regression equations that correlate log K_{ow} with plant bioconcentration; it is a mechanistic model that accounts for major plant processes and requires only a few well-known input data. Moreover, it was designed as a risk assessment tool and has been validated for the herbicide bromicil and several nitrobenzenes. A follow-on model (PLANTE) has recently been made available that also incorporates plant uptake during transpiration (i.e., accumulation directly from the air). The results on bromocil, nitrobenzene, etc., as well as ongoing validation studies suggest that the PLANT models may be a scientifically defensible alternative to the uptake-response slopes generated by log K_{ow} regressions.

G.9 Conclusions and Recommendations

The comparison of generic plant SSLs with generic SSLs for soil ingestion and migration to ground water indicate that the soil-plant-human exposure pathway may be of concern for two of the six metals evaluated (arsenic and cadmium). For mercury, nickel, and selenium, SSLs based on the other pathways are likely to be adequately protective of the soil-plant-human exposure pathway. In addition, data presented on the phytotoxicity of these metals and zinc suggest that toxic effects in plants are likely to be observed below levels that would be harmful to humans. Although this pathway

may not be of concern from a human health standpoint, these data suggest that metals could be of particular concern for ecological receptors.

Currently, EPA is developing methods to evaluate the uptake of organics into plants. In addition to the efforts of the Office of Solid Waste and the Office of Research and Development mentioned in the Introduction, OERR has jointly funded research on plant uptake of organics with the State of California. These studies support ongoing revisions to the indirect, multimedia exposure model, CalTOX. Until these efforts are reviewed and finalized, OERR will continue to address the potential for plant uptake of organics on a case-by-case basis.

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