CSAP Technical Guidance for

Soil Sampling Depth to Characterize Ecological Exposure

MOE Policy Decision Summary Issue 11

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Issue Definition

Protocol 1 (Landis et al. 1998) states that collection of soil samples to a depth of 15 cm is appropriate for characterizing plant exposure as well as soil invertebrates. However, current practice (e.g., Screening Level Risk Assessment, Protocol 13) is usually based on the surface 1 m to characterize plant and animal exposure to contaminants in soils. A technical review of factors that affect this exposure pathway is needed, to recommend policy on the depth of soil required to characterize exposure in support of ERA.

Note that it is expected that horizontal and vertical delineation of contamination will have been accomplished through site investigation and preparation of a detailed site investigation.

Disclaimer/Limitation Statement

This document does not constitute regulatory guidance or policy. It is the intent that this document will be used by members of the Society of Contaminated Sites Approved Professionals (CSAP) of British Columbia conducting reviews of sites/reports for which they may be making recommendations in accordance with BC Ministry of Environment (BCMOE) Protocol 6: Eligibility of Applications for Review by Approved Professionals.

The guidance provided in this document reflects what is considered good practice for conditions found at most sites. The guidance is based on the current regulatory regime and scientific methods, and hence may be updated as new information becomes available. Please note that the guidance may not be applicable to all sites, and therefore that sound professional judgment must be applied to ensure that the guidance is applicable to the particular site/report under consideration.

Issue Analysis

A pathway analysis for soil exposure to invertebrates, plants and vertebrates (see Figure 1) shows how the various receptors are exposed to soil. While all pathways should be screened for inclusion in the ERA, vapour exposure is typically not included as a pathway unless there are burrowing vertebrates present at the site. Also, the influence of contaminated soil (at any given depth) on groundwater-related pathways is not addressed here.

Overview

To support determination of the depth of soil required to characterize exposure for a receptor in an ERA, these three steps are required – each of which is discussed in more detail below:

1. Problem formulation
2. Evaluate exposure
3. Risk management to address soil pathways

Problem Formulation

As part of the overall ERA problem formulation, the planning process should address soil depth. The reader is referred to this guidance and advised to also take into consideration land use (present and future):

- Detailed Ecological Risk Assessment (DERA) in British Columbia Technical Guidance (Science Advisory Board, 2008)
- Federal Contaminated Sites Action Plan (FCSAP) Ecological Risk Assessment Guidance (Environment Canada, 2012)

- CSR Protocol 13[1] - the definition of “potential terrestrial habitat” can be used to infer MOE policy on the surface areas of sites, related to land use,that would be considered habitat and meriting evaluation. Section 3 and Form B-3 of Protocol 13 may also be useful to define habitat suitability for undeveloped land.

Specific objectives of the risk assessment should be incorporated into the sampling design where applicable. For example, if the objective is to assess potential risk through direct exposure to soil contaminants, it may be appropriate to define a "surface" soil layer of specified thickness as the unit of interest. The precise definition of surface soil will vary from site to site, depending on land use and the risk assessment assumptions. Due to SLRA guidance (Protocol 13) and site-specific decisions over the past number of years in BC, one meter (1 m) has become a default assumption under the CSR. The federal regime (CCME 2006, CCME 2008, Environment Canada 2012) considers: (1) the interval from “grade” to 1.5 m below grade as accessible for direct contact by ecological receptors and (2) the ecological soil contact pathway may be eliminated for soils below 3 m depth.

The depth of soils to which receptors are exposed has been standardized in some regimes (e.g., default values based on policy determination), but exceptions arise. Several examples of exceptions are described in Environment Canada (2012), as follows. The relevant soil depth may be deeper where deep-rooting plants are present. Alternatively, if a site lacks deep-rooting plants (or has a planned future use that excludes them), soil depths characterizing exposure could be shallower. As another example, some COPCs or receptors may be associated only with the humic soil layer and not with the underlying inorganic soil layer. In that case, the depth used for exposure assessment may not be a fixed depth, but may vary site-specifically depending on the thickness of the humic layer. For some ERAs, soil at greater depth(s) will be explicitly considered in the ERA if there is a plan or a possibility for that soil become exposed (e.g., through removal of surface soils for site development).

The outcome of exposure assessment (described below) is information that can be matched with effects measures to estimate/describe risks. It is critical that the risk assessor conceptualize the exposure and effects information at the same time (during problem formulation) to ensure that they can be integrated effectively and to ensure that all information and ancillary data needs are identified prior to data collection.

Evaluate Exposure

The general purpose of exposure assessment is to characterize the mechanisms by which receptors are exposed to COPCs, and to quantify or categorize the magnitude of those exposures. This guidance focuses on characterizing external exposure to contaminants in soil via three steps, detailed below:

Step 1: COPC Identification

Identification of contaminants of potential concern (COPCs) (e.g., soil contaminant concentrations which exceed numerical standards or other relevant screening values for given contaminants) takes place in the site assessment process, prior to the ERA. COPC selection should be based on methods described in various MOE guidance documents and in CSAP Technical Review 11[2]. Importantly, the depth of soils considered for screening COPCs in the detailed site investigation may not be the same depth that is considered during exposure assessment for each receptor group.

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[1] This protocol is under review by MOE and changes with respect to habitat may be forthcoming.

[2] http://www.csapsociety.bc.ca/sites/fusebox.313web.com/files/CSAP%20Technical%20Review%20%2310%20-%20COPC%20Screening%20-%20%202012FEB17.pdf

Step 2: Receptor Selection and Determination of Relevant Soil Depth(s)

Receptor selection drives where in the soil horizon exposure to COPCs takes place (i.e., determination of the relevant soil depths for each receptor). Receptor selection for ecological receptors should be based on technical considerations as laid out in DERA (SAB, 2008) and Environment Canada (2012). Site conditions (current and future) need to be taken into account, for example, presence of paving, landscaping, site structures, etc.

Relevant to receptors with direct soil contact, the depth of bioturbation due, for example, to burrowing insects, burrowing vertebrates, and plant root systems will drive selection of relevant soil depth(s). Based on the selected receptors of concern, the depth of soil required to characterize exposure for a given receptor (or receptor group) can be defined. For this purpose, having the opinion of a biologist on site-specific rooting depths, insect activity depths, the probability of burrowing vertebrates, etc. can be important to provide the rationale for selected soil depths. These should be illustrated in the conceptual site model during problem formulation.

Three reviews were prepared in the form of technical appendices:

- Appendix A: Plant Uptake of Contaminants from Soil – reviews plant uptake of selected contaminants by plants from soil and then categorizes them as ‘limited uptake’, ‘limited translocation’, ‘readily taken up, highly phytotoxic’ and ‘readily taken up, bioaccumulative’. This information may be useful in initially identifying the most important COPCs for consideration in the ERA and/or identifying where the pathway for a given COPC may be negligible. For a given ERA, more definitive review may be necessary to exclude a COPC from further consideration. If it can be credibly argued that a given COPC is not bioaccumulated in plants, then this pathway can be excluded from further consideration.

- Appendix B: Rooting Depths of Plants – reviews rooting depth of plants present in Canada (particularly British Columbia). The goal of this search was to evaluate soil depths to which plant roots extend (i.e., is soil at depth of X meters representative of the soil depth in which plant roots are exposed to contaminants?). The literature search was not exhaustive; it was evident that rooting depths can reach significant depths. It is noted that, while rooting depths characterize potential exposure, most plants have the majority of their roots nearer the surface and the maximum rooting depths often describe where only trace amounts of roots are present. This review made it apparent that many plants have root depths that extend several meters, beyond the zone typically considered to represent surface soil. This is consistent with the precluding condition in Protocol 13 in which the presence of deep-rooting vegetation (> 1 m) means that SLRA cannot be applied.

- Appendix C: Burrowing Depths of Vertebrates and Soil Invertebrates – reviews literature on burrowing depth. Burrowing and soil disturbance depths for vertebrates varied from 0.26 m to 2.3 m. Burrowing depths for soil invertebrates were not reviewed in detailed, but depths range from the top few cm to greater depths including notable extremes (Harvester ants at 2.4 m; earthworm *Lumbricus* spp. at 2 m).

NOTE TO READER: The reviews presented here and in Appendices A to C are not exhaustive and should only be considered illustrative. The onus is on the risk assessor to provide their own rationale for soil depths that are used to characterize exposure for receptors at a given site.

In addition, the list below provides considerations to take into account when determining the appropriate soil depth to characterize exposure for a given receptor:

- Depth of water table (for example, a deep water table may cause plants to develop deeper rooting systems, or vice versa, or to preferentially develop below in the water table (e.g., willows); a shallow water table may preclude burrowing vertebrates)

- Differentiation of soil types within the soil horizons (e.g., humic soil layer overlying mineral soil; the humic layer is more likely to be the receptor's preferred habitat)

- Soil characteristics (moisture, grain size, porosity, percent organic matter, pH, cation exchange capacity, redox potential, soil texture/composition) within the soil horizons, which may drive the receptors' vertical distributions. See the United States Environmental Protection Agency's Ecological Soil Screening Levels document[3] for review.

- Fill materials and/or physically-disturbed area (e.g., gravel roads/parking areas, unpaved works yards) may need specific consideration as their nature can inherently compromise habitat quality for both invertebrates and plants.

- Source of soil contamination and its spatial distribution relative to the receptor (e.g., spill, deposited on surface, groundwater contamination, covered by fill, etc.).

- Soil pH (potentially reflective of vertical COPC mobility and COPC availability)

- Nature of habitat, for example, disturbed vs. native and urban vs. wildlands settings.

- Presence of deep-burrowing soil invertebrates (e.g., earthworms, harvester ants)

- Presence of burrowing vertebrates; unconsolidated soils can attract burrowers, and/or facilitate burrowing to depths greater than average

- Presence of deep-rooting vegetation (in BC, based on Protocol 13 described as roots extending > 1 m). Where deep-rooting vegetation does or will exist, specific consideration in the ERA should include:
  - The likelihood that the plants will uptake the COPCs (Appendix A) and - if they do - To what tissue concentrations? To what effects to the plants, as well as to effects to plant consumers and the associated risks?
  - The vertical overlap of contaminant concentrations with rooting depth (Appendix B) and the distribution of majority of the root mass relative to the contamination
  - The horizontal overlap of contaminant concentrations with the majority of root mass
  - The scope for risk management measures for deep-rooting vegetation (see below in this review)
  - While literature was not identified by this review that drew a relationship between the physical overlap of root mass and contamination, it is assumed that such a relationship would exist (i.e., uptake is proportional to root mass).

- For sites where the soil to plant pathway is potentially very important, and exposure to soil contamination can't be ruled out (i.e., rooting depth does, or will in the future, overlap with soil contamination), the risk assessment may have to assess exposure in other ways:

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[3] http://www.epa.gov/ecotox/ecossl/

  - If plants and/or soil invertebrates are present under current conditions, collect vegetation for chemistry analysis to directly measure exposure.
  - If vegetation cannot be collected, consider (1) literature review (e.g., documentation that the bioaccumulation in the plant does not need to be further considered because the COPC is translocated and volatilized out of the plant (e.g. during phytoremediation of VOCs; pathway is open but not significant), (2) modeling (document rationale and approach), and/or (3) collecting site soil in which to germinate and grow plants (i.e., soil bioassays), and then analyzing plant tissue samples for contaminant concentrations.

While there is a desire to have BC establish prescriptive guidance for soil depths representing different receptor groups, review of the literature (Appendices B and C) and discussion with practitioners does not support specification of such values for most receptors. Therefore the recommended approach is to:

1. Use a default of 1 m for soil invertebrates, or another depth that is site-specifically defensible and for which rationale is provided in the ERA.

2. For other receptors, require that risk assessments provide and document the site-specific rationale for the soil depths that are used to characterize exposure, taking into account the considerations identified above. The rationale could include literature information, site-specific empirical data, and/or professional judgment.

3. In the absence of information to indicate that contamination deeper than 3 m is linked to unacceptable effects, a default of 3 m shall apply, beyond which the ecological soil pathway is considered eliminated.

Step 3: Soil Exposure Characterization

Vertically and horizontally, the soil data that are used to characterize exposure must be data that are relevant for a particular receptor group. For each COPC-receptor combination, soil data representing exposure can be characterized using the maximum concentration, the mean, an upper confidence limit on the mean, or a selected percentile, depending on the quantity of samples, receptor characteristics, and the degree of conservatism appropriate for the ERA. The rationale must be detailed in the ERA. It may be important to plan the site investigation to collect exposure data in addition to “typical” soil data collection for purposes of delineation.

Risk Management to Address Soil Pathways

It is an option to apply risk management measures that preclude the need to evaluate a specific pathway; these can be are linked to conditions on a Certificate of Compliance (COC) or Approval in Principle (AIP). Typical examples of these risk management measures include:

- Current presence (COC) or future placement (AIP) of an impervious layer at the site (e.g., pavement), either as part of the development or with the intent of closing an exposure pathway.
- Landscaping plans that avoid development of deep-rooting vegetation in soils that are contaminated in the exposure zone.
- Placement of clean fill and/or topsoil over contaminated soils, to close exposure pathways for receptors.

From a philosophical perspective, the physician’s edict “cause no harm” and the phrase “the cure shouldn’t be worse than the disease” apply. The remedies employed at contaminated sites should not cause more harm than the contamination they are intended to address. That perspective should be a factor taken into consideration during remediation planning.

The MOE has indicated to CSAP that they will entertain retention of existing habitat to accommodate contamination that poses low risks, particularly in situations where contamination will attenuate. In these cases, agreement should be sought a priori from MOE and it is likely that monitoring would be required to confirm risk predictions.

In addition, while plants and immobile soil invertebrates may be affected locally by elevated COPC concentrations at a single soil sample location, the spatial scale at which potential major risk management measures would be implemented is also relevant. In other words, exposure (and risks) for plants and soil invertebrates should be understood at scales of exposure, risk and remedy - because spatial scale is an important element of the magnitude of any risk(s).

If site proponents employ measures to mitigate risks (or potential risks, if those measures are assumed for an ERA to close a soil exposure pathway) related to soil exposure, than risk-based considerations could be used in design of those risk management measures. While risk assessors should advise the development of a risk management plan, it is not their responsibility to design remediation measures that preclude or reduce soil contact (e.g., cap design).

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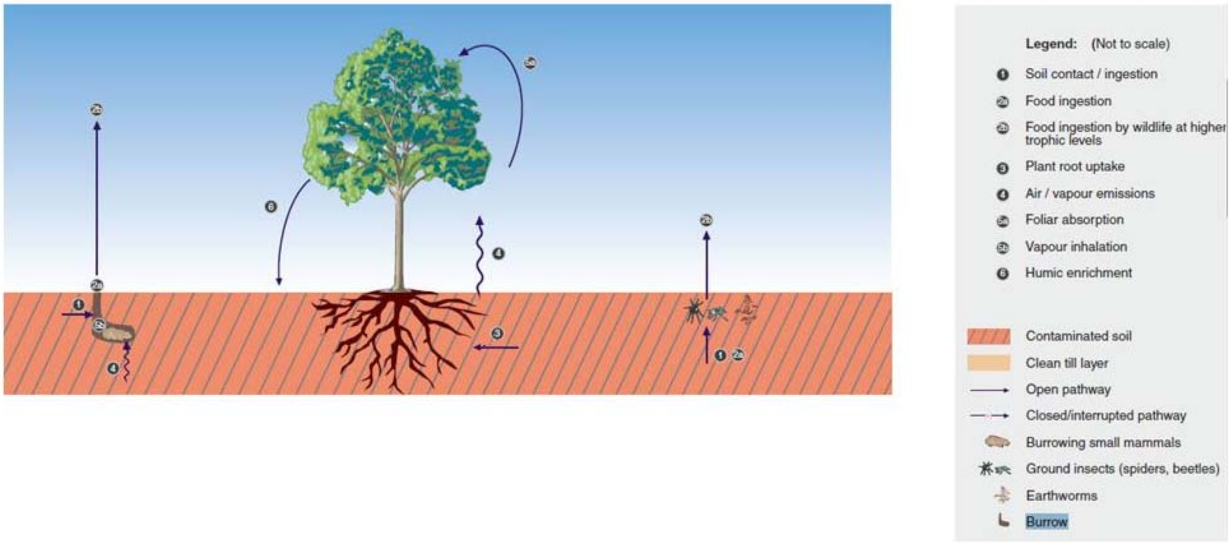

Figure 1: Generic conceptual site model for soil exposure to soil invertebrates, plants and burrowing vertebrates.

Appendix A: Uptake of selected contaminants by plants

Disclaimer

The review presented here is not exhaustive and should only be considered illustrative. The onus is on the risk assessor to provide their own rationale to characterize exposure for receptors at a given site.

Metals

The kinetics of metals uptake into plants are controlled by a variety of processes, including passive movement of metal into the root (non-energy requiring), passive movement of metals in response to an electrochemical gradient established by energy, and active metal uptake against an electrochemical gradient which also requires energy (McLaughlin 2002). Once taken up by the root, dissolved metals flow through both the symplastic and apoplastic routes to the stele. Specific to cationic metals, transport can be due to the large negative electrochemical potential produced by hydrogen ion translocating adenosine triphotphatase (ATPase) that maintains a gradient by pumping H^+ out of the cytoplasm of the cell, allowing metals to cross the cell membrane (McLaughlin 2002). Translocation of the metal ions occurs possibly at calcium/magnesium channels, or through facilitated transport through the enzyme ferric reductase (McLaughlin 2002). A second possible mechanism of metals uptake is through the transport of metal-chelate complexes. Chelating agents are released by the plant roots, and then the metals complex is taken up via facilitated transport (McLaughlin 2002). This latter method of uptake is unlikely to be a factor in soils contaminated by metals, as the plant only produces the chelating compounds in response to deficiency in essential metals.

A variety of factors affect the availability of metals to plants. Physiological factors that affect metals uptake by plants include the rate of root growth, which dictates the incidence of encounter with metals, and transpiration rates, which influences the amount of metals taken up in solution. These physiological factors are affected by environmental conditions such as nutrition, temperature and humidity. Soil conditions such as pH and organic content regulate the availability of metals to the plant. Aging can immobilize metals, making them less bioavailable to plants.

Organic compounds

Soil contamination by organic compounds can result in potential uptake and accumulation in terrestrial plants. The degree to which uptake and accumulation occurs is both a function of the physio-chemical properties of the compound in question, and the physiology of the plant species present. Non-ionizing organic compounds de-adsorb from organic carbon in the soil at a ratio that is a function of the octanol-carbon partition coefficient (K_{oc}), and transfer readily into plant tissues. Uptake into plant roots occurs via passive diffusion, and accumulation is a function of the lipid content in the roots. Very hydrophobic compounds diffuse slowly into the root, and are more likely to be trapped in the peel of root vegetables (Trapp 2002). Wild and Jones (1992) showed that nonionizing organic chemicals with a log octanol-water partition coefficient (K_{ow}) of >4 have a high potential for retention in plant roots, as they partition strongly into the lipids in the cells of the root. Less hydrophobic organic compounds are readily translocated from the root to the shoot of the plant, penetrating the epidermis, transversing the root cortex and crossing the endodermis and pericycle, where they are then transported throughout the plant via xylem flow. Partitioning of organic contaminants between roots and shoots is linearly related to K_{ow} (Collins et al. 2005); for extensive translocation, the ideal log K_{ow} is approximately 1.8 (Briggs et al. 1982).

Plant Biotransformation of Organic Contaminants

Plants may contribute to the dissipation of organic contaminants through metabolic breakdown (biotransformation). Studies have shown that PAHs can be biotransformed extensively by mycorhizae (fungus associated with plant roots) (Binet et al. 2000b). This symbiotic relationship between fungus and plant form the dominant means of PAH dissipation from soil (Binet et al. 2000b). Plants may facilitate the process of PAH dissipation by increasing microbial numbers, improving physical and chemical soil conditions, and increasing humification and adsorption of pollutants in the rhizosphere (Binet et al. 2000a). Testing showed that 3-6 ring PAHs were broken down by ryegrass (resulting in lower concentrations in shot tissue versus root tissue), but ageing of PAHs decreased dissipation (by metabolism) (Binet et al. 2000b; Binet et al. 2000a). Chlorinated organic contaminants have also been shown to be broken down by plants. Newman et al (1997) showed that poplar trees were capable of uptake of trichloroethylene (TCE), and breakdown of TCE resulted in trichloroethanol, trichloroacetic acid and dichloroacetic acid. The capability of plants to take-up and biotransform PCBs is limited, but symbiotic relationships between bacteria and four plant species (tobacco, horseradish, nightshade and alfalfa) showed that plants were able to breakdown the metabolites of bacteria and vice versa (Macková et al. 2007). Toxic and bioaccumulative effects of contaminants on plant species may be mitigated by biotransformation by plants and associated microflora.

Table 1: Uptake (indicated by a ✓) by plants of metals and organic contaminants. Categorizations ('limited uptake', 'limited translocation', 'readily taken up, highly phytotoxic' and 'readily taken up, bioaccumulative') were based on Chaney (1980) and McLaughlin (2002) for metals and Wild and Jones (1992) for organics. Absence of ✓ does not indicate absence of uptake.

Contaminants	**Limited uptake**	**Limited translocation**	**Readily taken up, highly phytotoxic**	**Readily taken up, bioaccumulative**	**Notes**
METALS					
Silver	✓				• Low solubility • Strong retention in soil
Chromium (III)	✓				
Gold	✓				
Titanium	✓				
Tin	✓				• High levels of tin can result in uptake, but not above soil levels (BCF<1)
Yttrium	✓				
Zirconium	✓				
Silicon	✓				
Fluoride	✓				
Arsenic		✓			• Strongly sorbed to soil colloids • Generally not readily translocated
Aluminum		✓			• Relatively insoluble in the root
Antimony		✓			• Sb(III) salts cross cell membranes through aquaporins • Sb(V)salts larger, can't cross membrane easily • In soil?
Mercury		✓			
Iron		✓			• Relatively insoluble in the root
Lead		✓			• Toxic to photosynthetic activity • Strongly sorbed to soil colloids (uptake only at excessive soil concentrations)
Boron					
Copper			✓		• Essential micronutrient, phytotoxic at high levels • Readily taken up by the plant from the soil • Efficiently translocated from the roots to

Contaminants	Limited uptake	Limited translocation	Readily taken up, highly phytotoxic	Readily taken up, bioaccumulative	Notes
					the shoots
Manganese			✓		
Nickel			✓		
Zinc			✓		• Plant can efflux at high concentrations
Cadmium			✓		• Translocated apoplastically • Sequestered in roots
Cobalt			✓		
Molybdenum				✓	
Selenium				✓	• Essential micronutrient • Chemically similar to sulphur, same uptake pathway • Integrated into proteins
Chromium (VI)				✓	• Highly toxic; affect photosynthesis, seed germination and plant growth • Taken up via same pathways as iron and sulfate
ORGANICS					
Polycyclic Aromatic Hydrocarbons					
Napthalene				✓	• Highly volatile
Phenanthrene	✓				• $K_{ow} > 4$; likely sorbed to soil particles or broken down by soil microbes
Fluoranthrene	✓				
Pyrene	✓				
Benzo[b]fluoranthrene	✓				
Benzo[a]pyrene	✓				
Benzo[ghi]perylene	✓				
Phthalate acid esters					
Butylbenzylphthalate	✓				• Readily biotransformed by soil microbes (Chao et al. 2006); as the side chain size increases, breakdown decreases
Diethylhexylphthlate	✓				
Di-n-butylphthlate	✓				
Di-n-octylphthlate	✓				
Surfactants					
LAS			✓		• Application on soils via sludge • Phytotoxic at high concentrations • Readily broken down by soil microbes (Guang-Guo 2006)
Nonylphenol		✓			

Contaminants	**Limited uptake**	**Limited translocation**	**Readily taken up, highly phytotoxic**	**Readily taken up, bioaccumulative**	**Notes**
Polychlorinate biphenyls					
Aroclor 1016		✓			- Uptake limited by large molecular size and high K_{oc}
Aroclor 1232	✓				
Aroclor 1248	✓				
Aroclor 1260	✓				
Polychlorinated dioxins and furans					
TCDD	✓				
Organochlorine pesticides					
Aldrin	✓				- Persistent in the environment (1237 days)
Dieldrin				✓	- Persistent in the environment (up to 1237 days for Dieldrin and 266 days for Lindane).
Lindane				✓	
DDT	✓				
2,4-D			✓		- Herbicide
pp-DDE	✓				
pp-DDD	✓				
Toxaphene				✓	- Persistent in the environment (up to 10 years)
Monocyclic aromatics					
Benzene				✓	- Volatile – route of plant exposure more likely to be deposition on leaves than through root uptake
Toluene				✓	
Xylene				✓	
Ethylbenzene				✓	
Chlorobenzenes					
Chlorobenzene				✓	- Plants readily uptake chlorobenzenes, and transfer from roots to shoots (Wang and Jones 1994)
Dichlorobenzene				✓	
1,2,4-Trichlorobenzene				✓	
Hexachlorobenzene		✓			
Short-chain halogenated aliphatics					
Chloroform		✓			- Half-life is less than 50 days, readily broken down by soil microbes
Carbontetrachloride		✓			
Trichlorethylene		✓			
Tertachloroethylene		✓			
Tetrachloroethane		✓			
Vinyl chloride		✓			

Contaminants	Limited uptake	Limited translocation	Readily taken up, highly phytotoxic	Readily taken up, bioaccumulative	Notes
Methyl chloride				✓	
Phenols					
Chlorophenol		✓			• Half-life in sludge is less than 100 days, (half life increases as the number and size of groups on the phenol increases), broken down by soil microbes.
2.4 – Dichlorophenol		✓			
Pentachlorophenol	✓				
Phenol		✓			
2,4-Dinitrophenol		✓			

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Appendix B – Rooting depths of selected plants of various types

Disclaimer

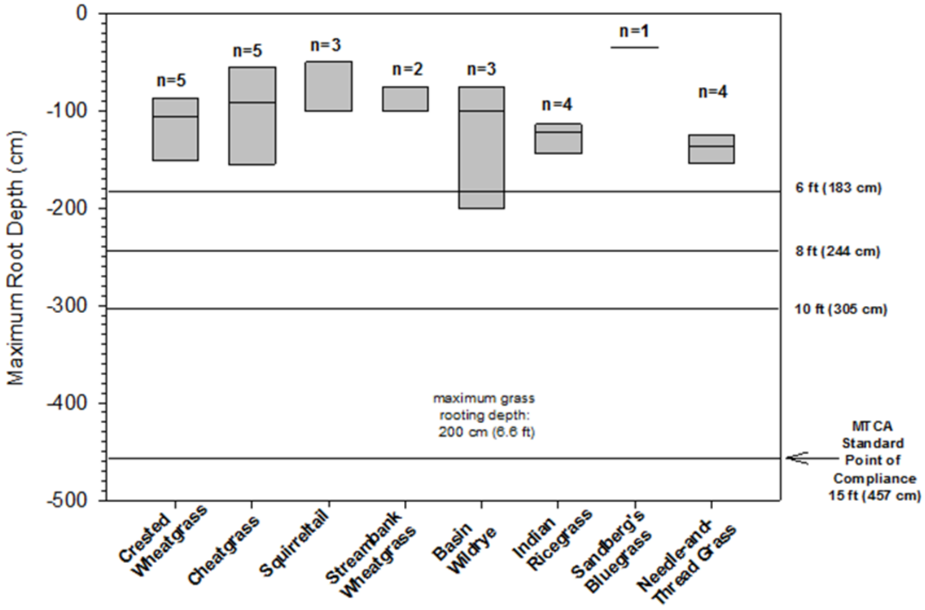
The review presented here is not exhaustive and should only be considered illustrative. The onus is on the risk assessor to provide their own rationale to characterize exposure for receptors at a given site.

A small-scale literature search was conducted to determine rooting depths of plants present in Canada (particularly British Columbia). The goal of this search was to evaluate soil depths to which plant roots extend (i.e., is sampling soil to depth of X meters (m) representative of the soil depth in which plant roots are exposed to contaminants?). The literature search was not exhaustive; as it is evident that rooting depths were trending to significant depths, discussion on policy is merited at this point before investing more effort in compiling rooting depth information.

Figures extracted from Sample et al (2011) were provided by Brad Sample but should not be used beyond this document without his express written permission.

The results of the literature search are shown in Table B-1. Plants were separated into type (tree, shrub, forb, grass) and habitat (Garden, Boreal Forest, Crops, Temperate Grassland, Tundra) for classification. Maximum depths were tabulated, to present the extreme scenarios. The majority of trees had maximum rooting depths of 1 m or greater (excluding seedlings), with depths reaching to 10.7 m for apple trees and 12.2 m for ponderosa pines. Many shrubs had rooting depths greater than 1 m; the shrubby cinquefoil and antelope bitterbrush are recorded to reach maximum depths of 3 m. Even forbs and grasses had species with rooting depths greater than 1 m; golden asters have a maximum rooting depth of 2.4 m, and some ryegrass species can root to depths of 1.8-3.5 m.

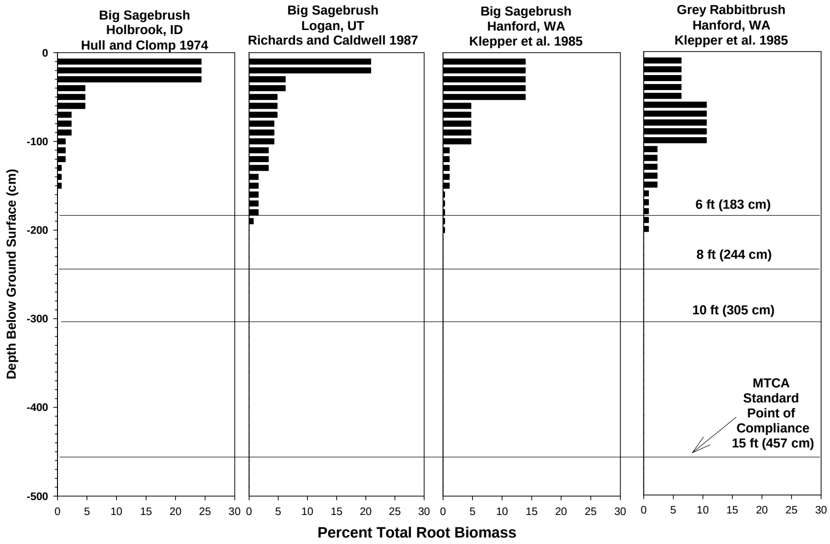
Sample et al. (2011) surveyed maximum rooting depth for forb, grass and shrub species (see example figure for grasses, below) to evaluate the suitability of Washington State's (Model Toxics Control Act) guidance of soil characterization to 15 feet.



Summary of Range of Observed Maximum Rooting Depths for Grass Species at the Hanford Site and INEEL.

For the species he surveyed (which were for habitats at the Hanford site, WA and did not include trees), plant roots typically did not extend beyond 2 m, but reached as deep at 3 m. Based on the data reviewed for this discussion paper, tree species in particular can extend to much greater depths.

It is noted that, while rooting depths characterize potential exposure, that most plants have the majority of their roots nearer the surface. Sample et al (2011) evaluated the vertical distribution of rooting and found that the vast majority of rooting in forbs, grasses and shrubs occurs nearer the surface. Sample et al's figure below is shown as an example of vertical distribution of rooting. At the maximum rooting depth for all plants, only trace root biomass is present.



Summary of observed distribution of root biomass by depth for shrub species present at Hanford.

Notes

The reference provided for the rooting depths for garden vegetables is from the BC Ministry of Agriculture, Food and Fisheries (2002). The depth given is not actually a measured rooting depth, but rather effective rooting depth (mature crops) for consideration in irrigation design. Effectively, this is likely the optimal depth from which the plant can draw up moisture so, if soil or water at this depth is contaminated, the contamination could be taken up into the plant. These values are included in the table as well for consideration.

Also included in this database, from Table 3.1 in "Tree Roots in the Built Environment" (Roberts et al. 2006) are rooting depths of various trees typically planted in urban and suburban settings.

For further information on rooting depths of trees world-wide, an excellent database was complied by Stone and Kalisz (1991).

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Table B-1: Rooting depths (m) for plant species, compiled from literature reviewed.

Plant	Species name	Type	Habitat	Rooting depth (m)	Reference
Cabbage	*Brassica oleracea*	forb	Garden	0.45	BC Ministry of Agriculture, Food and Fisheries, 2002
Cauliflower	*Brassica oleracea*	forb	Garden	0.45	
Cucumbers	*Cucumis sativus*	forb	Garden	0.45	
Lettuce	*Lactuca sativa*	forb	Garden	0.45	
Onion	*Allium cepa*	forb	Garden	0.45	*Note "rooting depth" really refers to depth of irrigation*
Radish	*Raphanus sativus*	forb	Garden	0.45	
Turnip	*Brassica rapa*	forb	Garden	0.45	
Beans	Fabaceae	forb	Garden	0.6	
Beets	*Beta vulgaris*	forb	Garden	0.6	
Blueberry	*Vaccinium corymbosum*	shrub	Garden	0.6	
Broccoli	*Brassica oleracea*	forb	Garden	0.6	
Carrot	*Daucus carots*	forb	Garden	0.6	
Celery	*Apium graveolens*	forb	Garden	0.6	
Potato	*Solanum tuberosum*	forb	Garden	0.6	
Pea	*Pisum sativum*	forb	Garden	0.6	
Strawberry	*Fragaria*	forb	Garden	0.6	
Tomato	*Solanum lycopersicum*	forb	Garden	0.6	
Fruit tree (various)	-	tree	Garden	**0.6 - 1.2**	
Brussel Sprouts	*Brassica oleracea*	forb	Garden	0.9	
Corn	*Zea mays*	forb	Garden	0.9	
Eggplant	*Solanum melongena*	forb	Garden	0.9	
Kiwifruit	*Actinidia delicioca*	shrub	Garden	0.9	
Pepper	*Capsium*	forb	Garden	0.9	
Squash	*Curcurbita*	forb	Garden	0.9	
Saskatoon	*Amelanchier alnfolia*	shrub	Garden	0.9	
Asparagus	*Aparagus officinalis*	forb	Garden	**1.2**	
Blackberry	*Rubus fruticosus*	shrub	Garden	**1.2**	
Grapes	*Vitis*	shrub	Garden	**1.2**	
Loganberry	*Rubus x loganobaccus*	shrub	Garden	**1.2**	
Raspberry	*Rubus*	shrub	Garden	**1.2**	
Sugar Beet	*Beta vulgaris*	forb	Garden	**1.2**	
Varied-Leaf Collomia	*Collomia heterophylla*	forb	Boreal Forest	0.26	Antos and Halpern 1997
Horseweed	*Conyza canadensis*	forb	Boreal Forest	0.33	
Smooth Hawksbeard	*Crepis capillaris*	forb	Boreal Forest	0.51	
Tall willowherd	*Epilobium paniculatum*	forb	Boreal Forest	0.52	
Tarweed	*Madia gracilis*	forb	Boreal Forest	0.23	
Woodland ragwort	*Senecio sylaticus*	forb	Boreal Forest	0.42	
Dwarf Oregon-grape	*Berberis nervosa*	shrub	Boreal Forest	0.8	
Fireweed	*Epilobium angustifolium*	forb	Boreal Forest	0.92	
Watson's willowherb	*Epilobium ciliatum watsonii*	forb	Boreal Forest	0.23	
Feltleaf everlasting	*Gnaphalium microcephalum*	forb	Boreal Forest	0.3	
Broadleaf lupine	*Lupinus latifolius*	forb	Boreal Forest	0.52	
Douglas fir (seedlings)	*Pseudotsuga menziesii*	tree	Boreal Forest	0.22	
Yerba de selva	*Whipplea modesta*	shrub	Boreal Forest	0.65	
Tamarack Larch	*Larix laricina*	tree	Boreal Forest	**1.2**	Canadell et al 1996
Jack Pine	*Pinus banksiana*	tree	Boreal Forest	**1.2**	
Jack Pine	*Pinus banksiana*	tree	Boreal Forest	**2**	
Lodgepole pine	*Pinus contorta*	tree	Boreal Forest	**3**	
Trembling Aspen	*Populus tremuloides*	tree	Boreal Forest	**2**	
Altai wild ryegrass	*Elymus angustus*	grass	Crops	**3.5**	
Russian ryegrass	*Elymus junceus*	grass	Crops	**1.8**	
Bromegrass	*Bromus imermis*	grass	Crops	**1.1**	
Pasture sage	*Artemisia frigida*	forb	Temperate Grassland	**1.7**	
Sagebush	*Artemisia cana*	shrub	Temperate Grassland	**2.4**	
Saltbush	*Atriplex nuttallii*	forb	Temperate Grassland	**1.8**	
Prairie Sandreed	*Calamovilfa longifolia*	grass	Temperate Grassland	**1.8**	
Golden aster	*Chrysopsis villosa*	forb	Temperate Grassland	**2.4**	
Winter-fat	*Eurotia lanata*	shrub	Temperate Grassland	**1.8**	
Common blanketflower	*Gaillardia aristata*	forb	Temperate Grassland	**1.8**	
Narrow-leaved blazingstar	*Liatris punctata*	forb	Temperate Grassland	**2.1**	
Rush sketelon plant	*Lygodesmia juncea*	forb	Temperate Grassland	**3**	
Shrubby Cinquefoil	*Potentilla fruticosa*	shrub	Temperate Grassland	**3**	
Red Cinquefoil	*Potentilla concinna*	forb	Temperate Grassland	**1.8**	
Golden bean	*Thermopsis rhombifolia*	forb	Temperate Grassland	**2.1**	
Northern wood-rush	*Luzula confusa*	grass	Tundra	0.3	
bluebunch wheatgrass	*Pseudoroegneria spicata*	grass	Temperate Grassland	**1.2**	Swan 2004

Table B-1: Rooting depths (m) for plant species, compiled from literature reviewed.

Plant	Species name	Type	Habitat	Rooting depth (m)	Reference
Sitka Spruce	*Picea sitchensis*	tree	Boreal Forest	**2.1**	Stone and Kalisz, 1991
Western Red Cedar	*Thuja plicata*	tree	Boreal Forest	-	
Lodgepole pine	*Pinus contorta*	tree	Boreal Forest	1	
Lodgepole pine	*Pinus contorta*	tree	Boreal Forest	**3.3**	
Tamarack Larch	*Larix laricina*	tree	Boreal Forest	**1.2**	
Jack Pine	*Pinus banksiana*	tree	Boreal Forest	**2.9**	
Ponderosa Pine	*Pinus ponderosa*	tree	Boreal Forest	**12.2**	
Douglas fir	*Pseudotsuga menziesii*	tree	Boreal Forest	**10**	
Western Hemlock	*Tsuga heterophylla*	tree	Boreal Forest	**1.9**	
Apple tree	*Malus*	tree	Garden	**10.7**	
Plum tree	*Prunus domestica*	tree	Garden	**4.9**	
Trembling Aspen	*Populus tremuloides*	tree	Boreal Forest	**3**	
Willow	*Salix*	tree	Boreal Forest	**3.6**	
Red alder	*Alnus rubra*	tree	Boreal Forest	1	Heilman, 1990
Bursage	*Ambrosia app*	forb	Shrub-steppe	**1.8**	Sample et al 2011
Russian thistle	*Echinops exaltatus*	forb	Shrub-steppe	**2.4**	
Basin Wildrye	*Elmus cinereus*	grass	Shrub-steppe	**2**	
Crested Wheatgrass	*Agropyrin cristatum*	grass	Shrub-steppe	**1.6**	
Cheatgrass	*Bromus tectorum*	grass	Shrub-steppe	**1.6**	
Needle-and-thread Grass	*Hesperostipa comata*	grass	Shrub-steppe	**1.6**	
Antelope bitterbrush	*Purshia tridentata*	shrub	Shrub-steppe	**3**	
Big sagebrush	*Artemisia tridentata*	shrub	Shrub-steppe	**2.5**	
Grey rabbitbrush	*Ericameria nauseosa*	shrub	Shrub-steppe	**2.5**	
Apple tree	*Malus*	tree	Urban plantings	**2.7**	Roberts er al, 2006
Ash	*Fraxinus*	tree	Urban plantings	**2.8**	
Beech	*Fagus*	tree	Urban plantings	**2.8**	
Birch	*Betula*	tree	Urban plantings	**3**	
Cedar	Cupressaceae	tree	Urban plantings	**2**	
Cherry	*Prunus*	tree	Urban plantings	**1.55**	
Chestnut	*Castanea*	tree	Urban plantings	**2.19**	
Cypress	Cupressaceae	tree	Urban plantings	**1.81**	
Douglas fir	*Pseudotsuga menziesii*	tree	Urban plantings	**1.45**	
False acacia	*Robinia pseudoacacia*	tree	Urban plantings	**2**	
False cypress	*Chamaecyparis*	tree	Urban plantings	**1.3**	
Fir	*Abies*	tree	Urban plantings	**2.17**	
Hawthorn	*Crataegus monogyna*	tree	Urban plantings	0.8	
Hazel	*Corylus*	tree	Urban plantings	0.75	
Hickory	*Carya*	tree	Urban plantings	**1.94**	
Holly	*Ilex*	tree	Urban plantings	1	
Honey locust	*Gleditsia triacanthos*	tree	Urban plantings	**1.72**	
Hornbeam	*Carpinus*	tree	Urban plantings	**2.1**	
Horse chestnut	*Aesculus hippocastanum*	tree	Urban plantings	**1.4**	
Indian bean tree	*Catalpa bignonioides*	tree	Urban plantings	**1.21**	
Larch	*Larix*	tree	Urban plantings	**2.2**	
Lime	*Citrus*	tree	Urban plantings	**2.6**	
Maple	*Acer*	tree	Urban plantings	**1.82**	
Mulberry	*Morus*	tree	Urban plantings	**1.5**	
Oak	*Quercus*	tree	Urban plantings	**2.05**	
Pine	*Pinus*	tree	Urban plantings	**3**	
Plane	*Platanus*	tree	Urban plantings	1	
Poplar	*Populus*	tree	Urban plantings	**2.43**	
Rowan	*Sorbus*	tree	Urban plantings	**1.35**	
Southern beech	*Nothofagus*	tree	Urban plantings	**1.58**	
Spruce	*Picea*	tree	Urban plantings	**2.14**	
Tulip tree	*Liriodendron*	tree	Urban plantings	**2**	
Walnut	*Juglans*	tree	Urban plantings	**2.14**	
Willow	*Salix*	tree	Urban plantings	**1.22**	
Yew	*Taxus*	tree	Urban plantings	**1.7**	

Appendix C – Borrowing depths of vertebrates and soil invertebrates

Disclaimer

The review presented here is not exhaustive and should only be considered illustrative. The onus is on the risk assessor to provide their own rationale to characterize exposure for receptors at a given site.

A compilation of burrowing and soil disturbance depths for vertebrates varied from 0.26 m to 2.3 m; some examples:

- Grizzly bears have been known to excavate dens for hibernation to depths of 2 m (Stevens and Gibeau 2005; Haroldson et al. 2002).
- Badgers will dig burrow in sandy loam soils to depths of 2.3 m (Sample et al. 2011).
- Smaller mammals such as the meadow vole, red squirrel, deer mouse, and the dusky shrew tend to have shallower burrows (<0.5 m) (Currier 1983; Nagorsen 2005; Rust 1946; Hamilton 1929; McCay 2000; Dawson et al. 1988; Getz 1961).
- Of special concern, burrowing owls (an at-risk species) use pre-existing abandoned burrows of badgers, prairie dogs, etc, and hence depth is dependent on what is available; burrow depths frequented by owls vary in depth from 0.26 m to 0.78 m (Royal BC Museum 2011).

Soil invertebrates can be classed on the basis of the depth of their penetration into the soil horizons (Coleman et al. 2004; Karaca 2010). Epigenic invertebrates reside on the surface of the soil, in amongst leaf litter and grass. Endogenic invertebrates such as *Lumbricus rubellus* inhabit the top 20 cm of the soil, while anecic species penetrate deeper; *Lumbricus terrestris* has been shown to burrow to depths of 2 m (Verhallen 2001). Sample et al (2011) reviewed invertebrate burrowing depths and for a specific site found that ants had the deepest soil penetration. Harvester ant, *Pogonomyrmex* spp., had mature colonies (up to 3 years) reaching depths of ~2.4 m and most soil was excavated from top 1.8 m and over half from top 25% of nest.

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Table C-1: Compilation of burrowing depth information for vertebrates.

ROC	Habitat type	Burrow depth	Description of Burrowing activity	Reference
Vertebrates				
Burrowing Owl	Open areas with low ground cover, existing burrows, and abundant food	0.26 - 0.78 m	Use abandoned burrows of Yellow-bellied Marmots, Belted Kingfisher, Striped Skunks, Prairie Dog, ground squirrels, badgers and occasionally Red Fox	Royal BC Museum, 2011
Belted Kingfisher	Near inland waterbodies or coasts in sandy banks	up to 0.150 m	Used as nest for laying eggs	Cornwell 1963
Garter Snake	Possible in most habitat types	0.15 m	Used during winter hibernation	Costanzo, 1985
Meadow Vole	Open fields and marshes	<0.5 m	Runways and dens tend to be close to the surface often in the litter layer	Getz 1961
Red Squirrel	In forested habitats and usually under pile of cones (midden)	0.471 - 1 m	Middens and caches	Patton and Vahle 1986, Earnest 1994
Deer Mouse	Coarse woody debris in most habitat types	<0.5 m	Not known to burrow extensively, although shallow or superficial burrows may be excavated in some populations. Uses existing cavities in rocks or under woody debris as dens or day	Dawson et al. 1988; McCay 2000
Dusky Shrew	Under coarse woody debris in most habitat types	<0.5 m	Burrowing unlikely to be extensive. Generally expected to be under coarse woody debris	Hamilton 1929; Rust 1946; Nagorsen 1996
Grizzly Bear	Usually deep soils on north-facing slopes at high elevations	2 m	Dens for winter hibernation	Haroldson et al. 2002; Stevens and Gibeau 2005
Red Fox	Possible in most habitat types	1.2 m	Dens	Sheldon 1950
Cougar	Possible in most habitat types	<0.5 m	Buries kills and scraps. Den sites tend to be in natural cavities, especially under woody debris	Currier 1983
Columbian Ground Squirrel	Open woodlands, forest edges, prairie, meadows, grassland	1 m	Usually under boulders, stumps or logs, 3-18 m in length	Hoodicoff, 1974
Yellow-bellied Marmots	Pastures, meadows, old fields with low vegetation	0.6 m	Consist of nest, flight and hibernating burrows	Hoodicoff, 1974
Northern Pocket Gopher	Nature grasslands, cultivated fields, roadsides and riverbanks	1.8-2.7 m	Maintain both living galleries and feeding tunnels (shallower levels)	Hoodicoff, 1974
Red-backed Vole	Dense understory mossy roten logs, brush	<0.5 m	May use abandoned burrows, but more often tunnel in soft litter under fallen logs or sphagnum moss.	Hoodicoff, 1974
Badger	Open grasslands, sandy loam soils	2.3m	Typically use a new den everyday, may use burrows abandoned by other animals	Sample et al, 2011
Striped Skunk	Possible in most habitat types	0.031-0.198 m	Dens for raising young	Allen and Shapton, 1942
Townsend's Ground Squirrel	Arid grasslands and shrub-grasslands	1.2 m	One squirrel per burrow, burrows may be grouped into colonies	Sample et al, 2011
Invertebrates				
Lumbricus terrestris	Possible in most habitat types	1-2 m	deep vertical burrows, structurally sound and likely permenant	Vanhallen, 2001
Lumbricus rubellus	Possible in most habitat types	0.03 m	horizontal burrows	Zorn et al, 2005
Epigenic invertebrates	Possible in most habitat types	-	Dwell on the surface of the soil, include springtails, macroarthropods etc.	Karaca 2010; Coleman Crossley Jr and Hendrix 2004
Endogenic earthworns - *Pontoscolex corethrusus*	Possible in most habitat types	0.02 m	burrows can be horizontal or vertical	Karaca 2010; Coleman Crossley Jr and Hendrix 2004
Harvester ant - *Pogonomyrex* spp.	Possible in most habitat types	2.3 - 2.7 m	Most soil excavated from top 183 cm	Sample et al, 2011