SOIL CONTAMINATION AND HUMAN EXPOSURE: A COMPREHENSIVE ASSESSMENT FRAMEWORK

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Soil is the thin outer zone of the earth's crust that supports rooted plants and is the product of climate and living organisms acting on rock. Throughout the world, soils are contaminated to some extent by local, regional, and global pollution sources of both natural and human origin. Sources of soil contamination are identified and discussed. With the possible exception of agricultural applications of pesticides and fertilizers, most contaminant releases to soil are not easily quantified and, as a result, remain highly uncertain. In establishing a comprehensive framework for human exposure to soil contaminants, it is revealed that such exposure occurs through multiple transfer processes. The process for linking human exposure to soil contact is considered and it is found that the magnitude and persistence of exposure depend not only on the level of soil contamination but also on physical and chemical properties of soil, chemical properties of the contaminant, and the frequency and duration of human factors such as occupational and recreational activities or the consumption of home-grown food, which result in direct and indirect soil contact. All of these factors possess some degree of variance that leads to probability distributions for representing total exposure and risk.

Keywords human exposure, persistence, soil contamination, transformation, transport

Throughout the world, soils are contaminated to some extent by local, regional, and global pollution sources of both natural and human origin. This article focuses on the exposure component of the risk assessment process for soil contamination. Specifically, it addresses pertinent topics dealing with the introduction and formation of toxic substances in soil, their movement within and between soil and adjacent environments, and the contact of humans and biota with those media. Principles, methods, and supporting data requirements for quantifying the effect of contaminated soils on human health are discussed.

Soil is the thin outer zone of the earth's crust that supports rooted plants and is the product of climate and living organisms acting on rock. A true soil is a mixture of air, water, mineral, and organic components (Horne, 1978). The relative mix of these components determines the value of the soil for agricultural and other human uses. This relative mix also determines, to a large extent, how a chemical added to soil will be transported and transformed within the soil. Soils are characteristically heterogeneous. A trench dug into the soil zone typically reveals several horizontal layers with different colors and textures. These multiple layers often are divided into three major horizons: (1) the A horizon, which encompasses the root zone and contains a high concentration of organic matter; (2) the B horizon, which is unsaturated, is below the roots of most plants, and contains a much lower organic carbon content; and (3) the C horizon, which is the unsaturated zone of weathered parent rock consisting of bedrock, alluvial material, glacial material, and/or soil of an earlier geological period (Bowen, 1979).

Soils are composed of three major phases—gases, liquids, and solids. The fraction by volume of soil that is gas ranges from 10% in clay soils to 25% in sandy soils and typically decreases with increasing depth (Jury et al., 1983; Bowen, 1979). The soil solution is mostly water but also includes dissolved minerals and nutrients. The volume fraction of soil that is liquid ranges from 10%, which is typical for sandy soils, to 40%, which is typical for clay soils (Jury et al., 1983; Bowen, 1979). The fraction of solid material in soil accounts for some 50% to 80% by volume and 75% to 90% by mass (Bowen, 1979). Soil solids include both mineral (i.e., the parent rock) and organic components, including humic acids and decaying matter. The organic phase of soil is defined by its organic carbon content. Whereas the mineral component of soil ranges from approximately 70% to 90% by mass, the organic carbon content of soil ranges from much less than 1% by mass for desert or sandy soils to as much as 5% by mass for clay soils and even as high as 10% or greater by mass for peat bogs (Jury et al., 1983; Bowen, 1979).

Soils exist where the atmosphere, the hydrosphere, the geosphere, and the biosphere all converge. Therefore, contaminants in soil can

affect human health and the environment through a complex web of interactions. The subsequent sections introduce three issues related to soil and human exposure: (1) the potential for soil contamination by chemical, biological, and radioactive contaminants; (2) the potential fate, including both transport and transformation processes, for contaminants in soil; and (3) the types of direct and indirect human and animal contacts with soil contaminants that can result in risks to human and ecological health.

SOIL CONTAMINATION

Contamination in the soil can occur through several different transfer processes: rain and dry deposition of contaminants from air; transfer to soil through the use of contaminated water for irrigating farms, gardens, or lawns; and by releases of contaminants inherent to the soil matrix through natural physical or biological processes (Layton et al., 1993). Metal species and radionuclides released from combustion processes or from volcanoes and persistent organochlorine compounds are examples of agents that can be carried globally in the atmosphere (Travis and Hester, 1991; Wania and Mackay, 1995). These releases can result in low levels of soil contamination due to deposition from the atmosphere. In contrast, pesticide use and the disposal of radioactive, biological, and chemical wastes can lead to much higher but localized levels of soil contamination (U.S. Environmental Protection Agency, 1989). Some natural sources of contamination internal to the soil include locally high concentrations of toxic elements (e.g., arsenic, lead), the production of radon in soils, and the replication of toxic organisms. In the subsequent sections, sources of soil contamination are identified and discussed.

Direct Application of Contaminants to Soil

Direct releases to soil most often occur in the form of pesticide, herbicide, and fertilizer applications; burial or land farming of domestic and industrial wastes; applications of sewer sludge to agricultural lands; and chronic releases from motor vehicles from the wear of brakes and tires and oil leaks. In addition, accidental discharges to the soil from storage tanks and miscellaneous spills during the transport of toxic substances also occur. Contaminant releases to soil are normally quantified in terms of mass per unit of area per unit of time. For example, pesticide applications to agricultural fields can range from less than 1 kg/ha to more than 20 kg/ha (Wauchope, 1978). With the exception of agricultural applications, however, most contaminant releases to soil are not easily quantified and, as a result, remain highly uncertain.

Deposition from the Atmosphere

Contaminants in the atmosphere can be transferred to soil directly either through dry deposition, wet deposition, or gas partitioning (Cullen, 1995). Atmospheric deposition also occurs indirectly through deposition to plants and animals whose chemical constituents ultimately become incorporated into the soil (Jones et al., 1991). Dry deposition is the process by which particulate matter settles out of the atmosphere and onto soil or plant surfaces. Contaminants that are attached to these particles are carried to soil through this process. Contaminants on airborne particles also are washed from the air to the soil with rain or snow by wet deposition of particles. Contaminants dissolved in the gas phase of air also can be transferred to soil or plants through a combination of wet deposition and chemical partitioning. Water-soluble contaminants in the air phase partition into water droplets and are washed out onto soil during rain or snow. This process is termed "wet deposition of a gas phase." In addition, contaminants that are water soluble can be transferred from air to soil through partitioning, which involves the diffusion of chemical from solution in air to solution in the soil water. Similarly, contaminants that are relatively insoluble in water but highly lipid soluble can be transferred from air to soil by partitioning in the organic phases of soil. In this process, the contaminants diffuse from solution in air to solution in the organic phase of soil. Finally, contaminants in air can be transferred from air to plant surfaces by dry deposition, wet deposition, and by partitioning into the lipid and water phases of plants. When the plants are mowed or age and shed leaves, residual contamination is transferred to soil.

Use of Contaminanted Water for Irrigation

The use of contaminated water supplies to irrigate farm lands, gardens, and lawns can result in the accumulation of persistent compounds in the irrigated soil. Organic contaminants with low water solubility, when introduced to the soil, bind to the organic carbon phase of the soil where they can be retained and accumulate for relatively long periods. Some metal species also can accumulate and persist in soil if their soil chemistry favors the binding of these contaminants into the mineral phase. Once deposited, metals persist in the soil unless transported off site.

Contaminant Sources Internal to the Soil

In some cases, the source of soil contamination is the soil itself. For example, soils rich in toxic elements such as selenium, arsenic, lead,

mercury, cadmium, and so forth provide their own source of contamination. In addition, soils rich in uranium and its radioactive decay product radium provide continuous long-term sources of the radioactive gas radon in soil (UNSCEAR, 1988). The radon can diffuse from soil into the air of buildings or into groundwater, with resulting radiation exposures to human and animal populations. Other possible internal sources of contamination are biological organisms, which may be either directly health threatening or which produce toxic chemicals. Although inherent sources of contamination exist in many soils, it is important to consider the rate at which these soil-borne contaminants are released into the surrounding environment. This rate can be greatly influenced by human activities that disturb the organization, structure or chemistry of the soil.

TRANSPORT AND TRANSFORMATION OF SOIL CONTAMINANTS

There are a number of competing processes that influence the fate of a soil contaminant. Table 1 is a list of some of the transport and transformation processes that are involved in determining the fate of soil contaminants. Once added to or formed in a soil column, a contaminant can be transported out of the soil column to another part of the environment or be transformed into some other chemical species or degradation product. Therefore, once a contaminant has been identified in the soil column, one also must determine whether that substance will (1) remain or accumulate within the soil column, (2) be transported by dispersion or advection within the soil column, (3) be physically, chemically, or biologically transformed within the soil (e.g., by hydrolysis, oxidation), or (4) be transported to another part of the environment by crossmedia transfer (e.g., volatilization, runoff, groundwater infiltration). This section provides an overview of the processes by which contaminants are transported in and out of soil layers and summarizes transformation processes.

Table 1. Processes by which contaminants are transferred to and from soils

| Gains	Losses
Diffusion from air	Diffusion to air
Diffusion from rooting zone soil	Diffusion to rooting zone soil
Washout from air by rainfall	Advection to rooting zone soil
Dry deposition of air particles	Soil solution runoff
Contaminant sources	Erosion (mineral runoff) to surface water
	Resuspension of soil particles
	Chemical/physical transformation

Transport Processes in the Soil Column

To understand how chemical species are transported in soil, it is important to recognize that the soil column can be viewed as having at least three distinct reservoirs for contaminants (Bowen, 1979). These reservoirs are (1) the surface soil layer, (2) the rooting zone, and (3) the deeper unsaturated zone. The nature of these soil components is introduced in the following sections. Figure 1 illustrates a typical vertical profile of soil composition and how this is divided into more simple characteristic regions.

The Ground Surface Soil Compartment

Studies of radioactive fallout in agricultural land management units reveal that, in the absence of tilling, particles deposited from the atmosphere accumulate in and are resuspended from a thin ground or surface soil layer with a thickness of 0.1 to 1.0 cm (Whicker and Kirchner, 1987). The ground surface soil layer is at the top of the A soil horizon. The ground surface soil layer typically has a lower water content, higher gas content, and often a higher fraction of organic matter than underlying layers. Contaminants in the surface soil layer are more likely than deeper soil contaminants to be transported horizontally to adjacent land units or nearby surface waters by mechanical runoff and soil solution runoff. Contaminants also are transferred vertically between the surface soil and overlying air by resuspension, deposition, and volatilization/diffusion and between the surface soil and the rooting zone soil by diffusion and infiltration. In addition, surface soil contaminants are susceptible to wind erosion, biodegradation, transfer to plant surfaces by rainsplash, and, in contrast to contaminants in deeper soil, surface soil contaminants are susceptible to chemical transformation by photolysis.

The Rooting Zone Soil

Rooting zone soil includes the A horizon and part of the B horizon below the surface layer extending to approximately 1 m in depth. The depth of plowing in agricultural lands ranges from 15 to 25 cm; however, the roots of most plants are typically limited to the first meter of soil depth. In addition, the diffusion depth below which a contaminant is unlikely to escape to the atmosphere by diffusion is approximately 1 m or less for all but the most volatile contaminants. The presence of clay in the rooting zone layer serves to retain water. As a result, soil water content in the rooting zone is somewhat higher than that in surface soils. Contaminants in rooting zone soil are transported upward by diffusion,
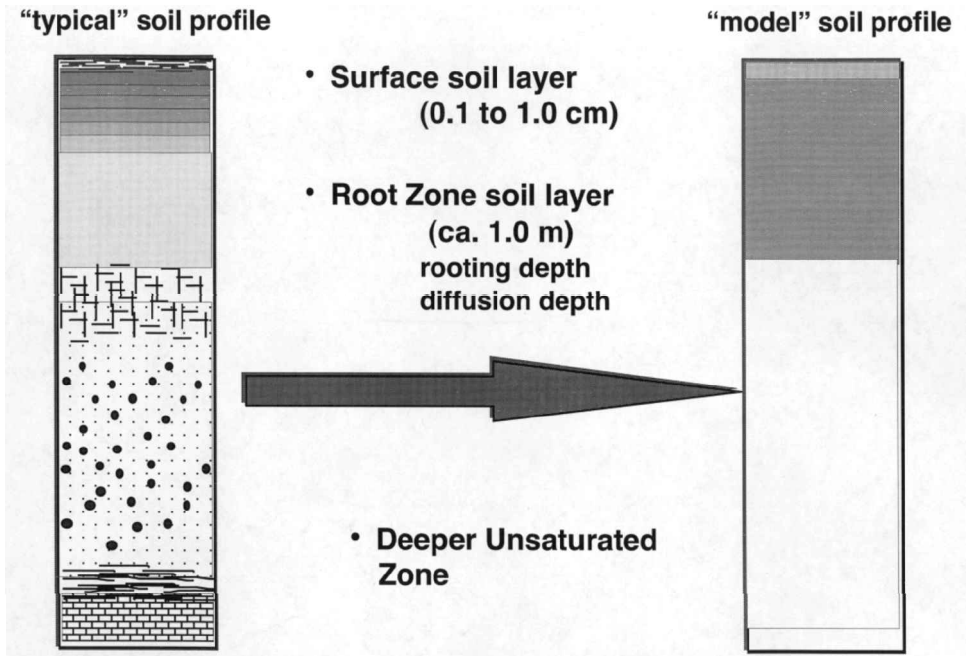
Figure 1. A typical vertical profile of soil composition and how this can be divided into more simple characteristic regions.

volatilization, root uptake, and capillary motion of water; transported downward by diffusion and leaching; and transformed chemically primarily by biodegradation or hydrolysis (Jury et al., 1983).

Deeper Unsaturated Soil

The deeper unsaturated soil includes the soil layers below the rooting zone and above the saturated zone, where all pore spaces are filled with water. This compartment can encompass parts of both the B and C soil horizons. The soil in this layer typically has a lower organic carbon content and lower porosity than the rooting zone soil. Contaminants in this layer move primarily downward to the groundwater zone by capillary motion of water and leaching. Chemical transformation in this layer occurs primarily by biodegradation.

Transformation

The transformation of toxic substances in soil can have a profound effect on their potential for human exposure and accumulation by biota. Transformation processes in soil include physical processes such as radioactive decay; chemical processes such as photolysis, hydrolysis, oxidation and reduction; and biological processes such as microbial transformations. All these processes can significantly reduce the con-

centration of a substance or alter its structure in such a way as to enhance or diminish its health effects (Larson and Weber, 1994; Lyman et al., 1982; Howard et al., 1978). Specific information on the rates and pathways of transformation for individual chemicals of concern must be obtained directly from experimental determinations or derived indirectly from information on chemicals that are structurally similar. Consequently, quantitative estimates are difficult to derive for classes of compounds for which empirical data are lacking. The following sections provide a brief discussion of the major transformation processes available to chemicals in the soil environment.

Radioactive Decay

Radioactive elements are made up of atoms in which the nuclei are unstable and give off atomic radiation as part of a process of attaining stability. The emission of radiation transforms radioactive atoms into another chemical element, which may be stable or may be radioactive such that it undergoes further decay.

Photolysis

Many organic contaminants are capable of undergoing either direct or indirect photolytic decomposition. Such decomposition can be partial, resulting in the formation of stable by-products, or complete, resulting in the destruction of the compound. Although solar radiation at the earth's surface is attenuated by the atmosphere, it is generally sufficient to break bonds in many compounds. In soils, phototransformation affects only those contaminants on the soil surface; however, the surface reactions may occur at significant rates in the presence of organic material. In addition, in agricultural lands that are tilled, contaminants in the tilling horizon (~ 20 cm) can be brought to the surface where phototransformation occurs. Phototransformations can result in relatively short half-lives (e.g., hours to days) for contaminants such as pesticides that are applied directly to crops or surface soils. Photolytic breakdown of pesticides can substantially reduce the concentrations of chemicals that are applied to crops and thereby diminish potential exposures to humans and animals that consume the crops. Photolytic breakdown also may occur by indirect or sensitized photolysis when humic material or mineral surfaces absorb light energy and transfer a portion of that energy to another chemical in the soil matrix.

Hydrolysis

Hydrolytic transformation of organic chemicals can be a significant destructive process for toxic compounds that are present in the aqueous phase of soils. Hydrolysis is most important for chemicals that have functional groups (e.g., amides, esters, carbamates, organophosphates)

that can be altered rapidly (e.g., in minutes to days) in the presence of water. For amides and carbamates, hydrolytic cleavage yields aromatic and aliphatic amines with an increased likelihood of toxic activity. Conversely, hydrolytic degradation of compounds that contain stable substituents (e.g., halogenated compounds such as carbon tetrachloride) can have half-lives of several thousand years. Because hydrolytic reactions are driven by the availability of hydrogen and hydroxide ions, the pH of the soil can have a dramatic influence on the rate of hydrolysis for any given compound. Hydrolytic transformations that are relatively slow at a neutral pH can occur at rates that are several orders of magnitude greater under acidic or basic conditions.

Oxidation and Reduction

Many inorganic and organic chemicals can undergo oxidation or reduction reactions in soil. An indicator of a compound's ability to be oxidized or reduced is provided by a knowledge of its oxidation potential, which is the voltage at which it is transformed to its reduced state. A similar measure of a soil's ability to reduce a compound is provided by the redox potential, which is a measure of electron activity. Redox potentials are relatively high and positive in oxidized environments (e.g., surface waters) and highly negative in reduced environments (e.g., aquatic sediments, the subsurface soil layers). These environmental conditions are especially important for inorganic chemicals that are rarely present in their elemental form in the environment. Arsenic, for example, exists primarily in its oxidized form (arsenate) in the atmosphere and in surface waters and in its reduced form (arsenite) in sediments.

Microbial Transformation

Because of their broad range of enzymatic capabilities, micro-organisms are capable of transforming many inorganic and organic compounds. Such transformations result in the partial degradation of a compound (e.g., conversion of trinitrotoluene to dinitrotoluene), mineralization (i.e., complete transformation to carbon dioxide and water), or synthesis of a stable product (e.g., formation of methyl arsenicals from arsenate). Although these processes generally result in the detoxification of the parent compound, toxic products or products with greater mobility in the environment also may be formed.

HUMAN CONTACT WITH SOIL

Human contacts with soil can be multiple and complex (McKone and Daniels, 1991; National Research Council, 1991). Table 2 lists a matrix

Table 2. Matrix of exposure pathways that link humans with contaminated soils through direct and indirect contact

Exposure Routes	Exposure Pathways Linking Contaminated Soil with Human Contact
Ingestion	Direct soil ingestion by humans
	Ingestion of fruits, vegetables, and grains contaminated by transfer from soil
	Ingestion of meat, milk, and eggs contaminated by transfer from soil to plants to animals
	Ingestion of meat, milk, and eggs contaminated through soil ingestion by animals
	Ingestion of groundwater contaminated by soil
Inhalation	Inhalation of soil vapors that migrate to indoor/outdoor air
	Inhalation of soil particles transferred to indoor/outdoor air
Dermal contact	Dermal contact with soil

of potential human contacts with soils than can result in human uptake of soil contaminants through inhalation, ingestion, and dermal exposure routes. In the following sections, what is known about some of these exposure pathways and how they might be assessed in a risk assessment or other health effects study are considered. Figure 2 provides an illustration of how contaminants migrate from soil into the media that compose the human environment.

Direct Soil Ingestion

Both adults and children continuously ingest small amounts of soil through inadvertent hand-to-mouth activities. Children who spend a great deal of time outdoors have been observed to have contact with and ingest soil. Through activities such as gardening, outdoor labor, and cleaning, adults are also subject to inadvertent soil ingestion. Some individuals have been observed to intentionally ingest rather large quantities of soil. The ingestion of nonfood substances such as soil is called pica. Geophagia is the intentional, chronic, and often addictive consumption of earth.

Several studies have been conducted to characterize soil ingestion by children (e.g., Calabrese and Stanek, 1991). Some studies make use of soil loading on children's hands in combination with observations of hand-to-mouth activity to estimate soil uptake. Another approach to estimating soil ingestion makes use of tracer elements in feces. Both the feces of children and the soil in their play yard are analyzed for elements such as aluminum, silicon, and titanium—elements thought to
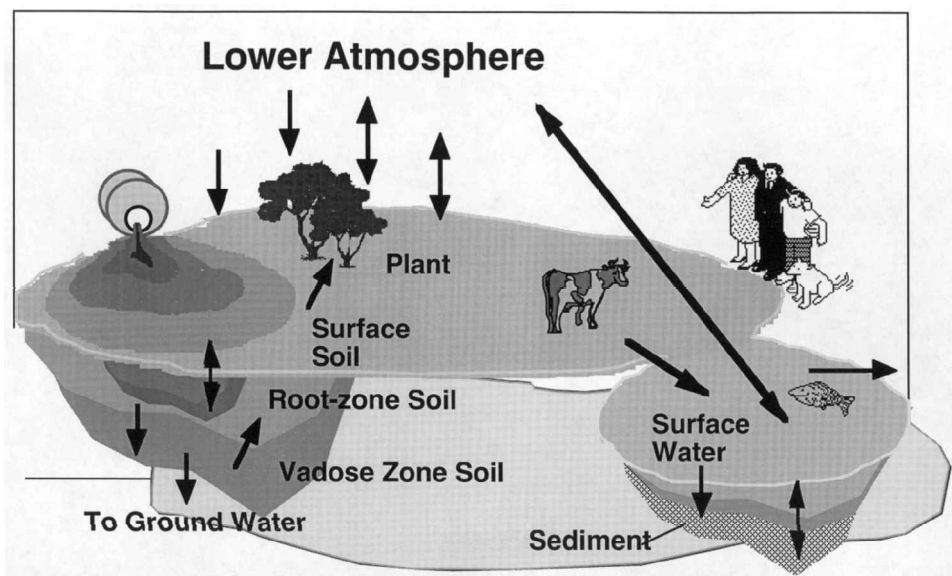
Figure 2. Contaminants migrate from soil into the exposure media that compose the human environment in the manner illustrated here.

be poorly absorbed in the gut. Assuming no nonsoil sources of these elements and a fecal excretion rate, soil ingestion for each child is estimated on the basis of the mass of each tracer element in feces relative to that in soil. Hospitalized children who have little contact with soil often are used as control groups.

Transfer of Soil Contaminants to Vegetation and Food Products

Soil contaminants can be transferred to edible parts of vegetation from the rooting zone soil by root uptake and from the surface soil layer by resuspension/deposition, rainsplash, and volatilization followed by partitioning (Jones et al., 1991). Contaminants in the rooting zone are transferred to plant roots from soil gas and soil liquid with potential transfer in the transpiration stream to above-ground plant parts. The ease with which nonionized chemicals are taken up from soil into root material is influenced by the chemical's octanol/water partition coefficient, K_{ow}, which is a commonly used measure of lipophylicity, and by the water solubility. Chemicals having high K_{ow} values tend to be either strongly bound to organic material in the root, making them less available for movement in the transpiration stream, or bound to organic material in the soil reducing their availability to root uptake. Increasing the water solubility of a chemical tends to increase the amount of chemical available for uptake from the soil water and

increases the likelihood of movement with the transpiration stream; however, the root membrane on most plants restricts uptake of highly soluble or ionized species.

Contaminants in the rooting zone can be transferred to surface soil by plowing and tilling or by the activities of burrowing animals such as worms, ants, and rodents. These contaminants then can be transferred to edible plant parts through resuspension/deposition, rainsplash, and volatilization/partitioning. Resuspension/deposition is the process by which soil particles are blown by the wind from the soil surface onto the leaves of vegetation. The soil contaminants can remain on the leaf surface for an extended period or be absorbed into the plant tissue where they may become available for transport to other parts of the plant. Rainsplash is a process through which the effect of falling rain drops causes soil particles to be scattered onto plant surfaces. Volatilization/partitioning is a two-step process by which contaminants with a sufficiently high vapor pressure volatilize from the soil and then collect into the waxy surface or the water portion of leaves through an air/lipid or air/water exchange.

Contaminants in vegetation can be transformed to food products. The level of contamination in vegetative food products often depends on which part of a plant is being consumed. Translocation, which is the process by which a contaminant is transferred from one part of a plant to another, can result in significant differences in contaminant concentration between the total plant and the part of the plant being consumed, that is, the fruit or seeds. In addition, ingestion by food-producing animals of contaminated soil and soil-contaminated pasture or grains can lead to the contamination of animal-based food products, such as meat, milk, dairy products, and eggs.

Dermal Contact with Soil

Dermal exposure to contaminants in soil can occur during a variety of activities, such as construction work, gardening, and outdoor recreation. Adults who work and children who play outdoors can have high soil loading on their skin. Lipid-soluble chemicals have a strong tendency to move from a soil layer on the skin surface to the lipid-rich outer layer of human skin. However, the rate at which this transfer takes place is often very slow and could require hours or even days to reach an equilibrium state. Estimating doses that result from contact with a contaminated soil involves many parameters that are often difficult to measure including the contaminant concentration in soil, the soil-to-skin adherence factor, the chemical-specific absorption factor for the skin–soil system, the exposure frequency, and the exposure time. The exposure frequency expresses how often, in days per year, that an

individual is involved in an activity that results in soil contact. The exposure time is a measure of how long in hours the soil is in contact with skin during an exposure activity.

Dose estimates for soil contact with skin are highly uncertain. In addition to uncertainty in the previously mentioned processes and parameters, uncertainty about the dose received through soil contact includes uncertainty about the transport of chemicals within the skin layer; the interaction of the soil layer on the skin with the skin surface; the dynamic conditions always involved in scenarios addressing interaction of the skin surface with chemicals, soil, air, and water; and the level of protection provided by clothing.

Inhalation Soil Particles Suspended As Dust

Soil contaminants that are bound to soil particles can be resuspended and inhaled along with the fine particles to which these contaminants are attached. Inhalation of suspended particles occurs both outdoors and inside buildings. In recent years, there has been recognition that a fraction of the fine and coarse particles in the indoor environment originates from outdoor sources. Soil enters the indoor environment by processes such as resuspension, deposition, and soil tracking. Soil tracking is the process by which soil particles are carried into the indoor environment by shoes and clothing of human occupants and by the feet and fur of pets. These outdoor sources typically account for about 20% to 50% of indoor particulates. The remainder is due to indoor sources such as cooking, smoking, carpet wear, and the sloughing of skin cells from humans and pets.

Contaminant Vapor Transport into Buildings

The vapor of volatile contaminants, such as radon and volatile organic compounds, can be transported through diffusion from the soil pore spaces into buildings. Three principal factors are needed to define the ratio of contaminant concentration in indoor air to observed contaminant concentration in soil gas: (1) the distance between the contaminant source and the building foundation, (2) the permeability of the soil, and (3) the area of cracks in the foundation relative to the total area of the foundation (Johnson and Ettinger, 1991).

Groundwater Contamination

Soil contaminants can be transformed by physical, chemical, or biological processes. Those that are not transformed can be carried to ground-

water in areas of net recharge. Once contaminants move from soil into groundwater, these contaminants can contact humans through a number of exposure pathways, such as direct water ingestion, dermal uptake in showers or baths, irrigation of crops, feeding food-producing animals, and so forth.

QUANTIFYING HUMAN CONTACT WITH SOIL-BORNE CONTAMINANTS

The objective of exposure assessment is typically to estimate the potential average daily dose (ADDpot) received by an individual in an exposed population. Exposure occurs through multiple environmental media, multiple exposure pathways, and multiple exposure routes. The estimated ADDpot is used along with a dose–response function to relate the potential dose to the lifetime probability of detriment or risk per individual within the exposed population. In general, the exposure assessment component of a risk assessment (1) identifies the chemical of concern and characterizes its sources and its distribution among the various environmental media, (2) identifies each potential exposure pathway and provides measurements or estimates of the concentration of contaminant in each of the various contact media, (3) estimates the frequency and duration of contact between the exposed individual and each contact medium, and (4) characterizes the uncertainty or variability inherent to the parameters used in the assessment process and the resulting uncertainty in the final estimate of dose.

Total Exposure Models

The source term or initial contaminant inventory in the soil layers is linked to the different environmental media through a multimedia environmental fate and transport model, such as a regional multimedia model (Cohen et al., 1990), a Mackay-type fugacity model (Mackay, 1991), or the transport component of the CalTOX model (McKone, 1993a, 1993b). This is illustrated in Figure 2. The environmental media concentrations are in turn linked to the various exposure media using intermedia transfer factors, as is done in the exposure component of the CalTOX model (McKone, 1993c). The exposure media concentrations are then transformed to dose using a multiple pathway exposure model that accounts for and quantifies human behavior patterns that result in contact with the exposure media. Finally, the dose is related to risk through a route-specific dose–response function. These steps are systematically linked in a total exposure model where the distribution of lifetime risk, H(t), is constructed for an exposure duration, ED, starting at some time, t, in the future such that

$$H(t) = C_S(0) \times \left\{ \sum_{\substack{\text{exposure} \\ \text{route} \\ j}} \sum_{\substack{\text{environ} \\ \text{media} \\ k}} \sum_{\substack{\text{exposure} \\ \text{media} \\ i}} \left[Q_j(ADD_{jki}) \times \left(\frac{ADD_{jki}}{C_k} \right) \times \Phi[C_S(0) \rightarrow C_k(t)] \right] \right\}$$

1

where $\Phi[C_S(0) \rightarrow C_k(t)]$ is a multimedia dispersion function that uses our current understanding of the world to transform the measured contaminant concentration in the soil at time zero, $C_S(0)$, into the contaminant concentration in environmental media k at time t in the future, $C_k(t)$; $Q_j(ADD_{jki})$ is the dose–response function that relates the potential dose by route j to risk; and ADD_{jki}/C_k is the unit dose factor for exposure route j linked to environmental compartment k by contact media i.

The unit dose factor is derived by relating the exposure to the concentration in environmental medium k, averaged over the exposure duration. The general exposure equation is

$$ADD = \left[\frac{C_i}{C_k} \right] \times \left[\frac{IU_i}{BW} \right] \times \frac{EF \times ED}{AT} \times C_k$$

2

where C_i/C_k is the intermedia transfer factor that describes the relationship between the concentration in contact media i (i.e., outdoor and indoor air, household dust, drinking and bathing water, homegrown vegetables) to the concentration in environmental media k (i.e., ambient air, surface water, surface soil, rooting zone soil, groundwater); IU_i/BW is the intake or uptake rate from contact media i per unit of body weight; and EF, ED, and AT are the exposure frequency in days per year, exposure duration in years, and average time in days, respectively.

The total risk (Eq. 1) can be used in a forward direction to estimate the risk at some time in the future resulting from a contaminant concentration currently found in the soil. In addition, the equation can be rearranged by solving for $C_S(0)$ and used in the reverse direction to estimate a soil concentration or target cleanup goal that will maintain the expectation of risk at some time in the future below a predefined target risk.

The true value for each parameter in the total exposure model is often unknown. This is due in part to heterogeneity (spatial or temporal variability) inherent to many of the parameters and in part to uncertainty or a lack of scientific knowledge. The overall variance in each parameter is characterized using individual probability density

functions that are assigned based on the current understanding of the system. This variance is then propagated through the calculations using available computer software. The outcome is then presented as a distribution of risk or target cleanup goal to support regulatory decisions related to contaminated soils.

Confronting and Reducing Uncertainty

Because of the high degree of variability often associated with parameters in the total exposure models, it may be necessary to take steps toward reducing uncertainty in the outcome distribution to provide information that will facilitate regulatory decisions. Given that the reliability of the probability density functions for the input parameters directly influences the reliability of the model output, resources should be directed toward improving the reliability of the most influential parameters in the model. This requires that the important contributors to outcome variance first be identified.

To identify the important contributors to outcome variance, repeated analysis or Monte Carlo simulations can be run to produce a distribution of model outcomes that captures the total variance attained when all uncertain parameters are treated stochastically (e.g., parameters defined as probability density functions rather than point values). Random noise about this distribution is then determined from a set of Monte Carlo simulations followed by a stepwise selection of individual parameters that, when treated stochastically, contribute the most to the total outcome variance. The parameter selection process continues stepwise, adding one parameter at a time until the selection of an additional uncertain parameter no longer results in a noticeable change in the outcome distribution. Resources then can be allocated toward field measurements or laboratory investigations designed to improve the reliability of those parameters found to be significant contributors to outcome variance.

CalTOX

One example of an exposure model that provides a total exposure framework is the CalTOX model developed for the California Department of Toxic Substances Control (DTSC). The DTSC within the California Environmental Protection Agency, has the responsibility for managing the state's hazardous waste program. As part of this program, the DTSC funded the development of the CalTOX program (McKone, 1993a, 1993b, 1993c). CalTOX is a set of spreadsheet models and spreadsheet data sets designed to assist in assessing human expo-

sures and defining soil cleanup levels at uncontrolled hazardous wastes sites. CalTOX addresses contaminated soils and the contamination of adjacent air, surface water, sediments, and groundwater. The components of CalTOX include a multimedia transport and transformation model, exposure scenario models, and add-ins to quantify uncertainty and variability. The multimedia transport and transformation model is a dynamic model that can be used to assess time-varying concentrations of contaminants introduced initially to soil layers or for contaminants released continuously to air, soil, or water. This model assists the user in examining how chemical and landscape properties affect both the ultimate route and quantity of human contact. Multimedia, multiple-pathway exposure models are used in CalTOX to estimate average daily doses within a human population. The exposure assessment process consists of relating contaminant concentrations in the multimedia model compartments to contaminant concentrations in the media with which a human population has contact, that is, personal air, tap water, foods, household dusts, soils, and so forth.

DISCUSSION

The purpose of this article is to consider the nature of soils, how soils are contaminated by human activities, how these contaminants are transported and transformed in the soil column, the types of human activities that could result in human exposure to soil contaminants, and methods for quantifying these exposures. Soils are complex systems that exist at the interface among atmosphere, biosphere, hydrosphere, and lithosphere. A true soil includes gas, water, mineral, and organic components. Potential human contacts with soil can result in inhalation, ingestion, and dermal uptake of soil contaminants through both direct and indirect exposure pathways. The magnitude and persistence of exposure depends not only on the level of soil contamination but also on the physical and chemical properties of soil, the chemical properties of the contaminant, and the frequency and duration of human activities, such as occupational and recreational activities or use of home-grown food, which result in direct or indirect soil contact. All of these factors possess some degree of variance that ultimately produces a distribution of risk or a target cleanup goal that supports regulatory decision making. If variance in the estimate of exposure is too large to support reliable regulatory decisions, resources can be directed toward reducing the variability of those parameters that contribute most to the outcome variance. The result is an improvement in both the precision in the exposure estimate and in the overall understanding of the science of exposure assessment.

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