Title
Pollution, Soil

Journal
Encyclopedia of Toxicology, 2nd Edition

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Publication Date
2005

LBNL-57938

SOIL: Contamination and Human Contact

A submission prepared for the

Encyclopedia of Toxicology

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December 2004

This work was funded in part by the US Environmental Protection Agency National Exposure Research Laboratory through Interagency Agreement # DW-988-38190-01-0 and carried out at Lawrence Berkeley National Laboratory through the US Department of Energy under Contract Grant No. DE-AC03-76SF00098

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INTRODUCTION

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. The relative mix of these components determines both the value of the soil for agricultural and other human uses and the extent to which chemicals or biological organisms added to soil will be transported and/or transformed within the soil. Soils are characteristically heterogeneous. A trench dug into the soil zone typically reveals several horizontal layers having different colors and textures. These layers and their generic structure are illustrated in Figure 1. These multiple layers are often 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.

<figure 1 first called out here>

In an ecological sense, soils exist where the atmosphere, the hydrosphere, the geosphere, and the biosphere all converge. Thus, contaminants in soil can impact human health and the environment through a complex web of interactions. The sections below provide an introduction to three issues related to toxicology and soil—(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 health.

SOIL CONTAMINATION

Throughout the world soils are contaminated to some extent from local, regional, and global pollution sources. Frequently, this contamination is the result of human and natural activities that involve the direct application of contaminants to soil. However, soil contamination also results from the transfer by rain and dry deposition of contaminants from air; by the transfer of contaminants through sewage-sludge (biosolids) applications; from the use of contaminated water for irrigating farms, gardens or lawns; or by the soil itself through natural physical or biological agents that provide a source of contamination. Metal species and radionuclides released from combustion processes or from volcanoes and persistent organic pollutants (POPs) migrate globally in the atmosphere and result in low-levels of soil contamination as a result of deposition from the atmosphere. Pesticide use and the disposal of radioactive, biological, and chemical wastes can lead to much higher but localized levels of soil contamination. Some sources of contamination, such local high concentrations of toxic elements, the natural production of radon in soils, and the replication of toxic organisms are not external but internal to the soil. In the sections below, sources of soil contamination are identified and discussed.

Direct Application of Contaminants to Soil

Direct releases to soil 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, resulting from the wear of brakes and tires as well as oil leaks. In addition, accidental discharges to the soil from storage tanks and miscellaneous spills during the transport of toxic substances can also occur. Contaminant releases to soil are normally quantified in terms of mass per unit area per unit time. For example, pesticide applications to agricultural fields, can range from under 1 kg/ha to over 20 kg/ha.

Deposition from the Atmosphere

Contaminants in the atmosphere can be transferred to soil either directly through dry deposition, wet deposition, and vapor partitioning or indirectly through deposition to plants, whose parts fall onto the soil. Dry deposition is the process by which particulate matter settles out of the atmosphere and onto soil and plant surfaces. Contaminants that are attached to these particles will be transferred to soil through this deposition process. Atmospheric contaminants on particles are also washed out of the air to soil with rain or snow in the wet deposition of the particles. Contaminants dissolved in the gas phase of air and not bound to particles can also be transferred to soil through a combination of wet deposition and chemical partitioning. Contaminants dissolved in air that are water-soluble are easily washed out during rain and snow. This is 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 diffusing 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 carried from air to soil through partitioning into 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 vegetation surfaces by dry deposition, wet deposition, and by partitioning into the lipid and water phases of plants. When the plants decay, lose leaves, or are mowed; residual contamination is transferred to soil.

Use of Contaminated Water for Irrigation

The use of contaminated water supplies to irrigate farmlands, 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 will migrate to the organic carbon-phase of the soil where they can be retained for relatively long periods. Some metal species can also accumulate and persist in soil if their soil chemistry favors the binding of these contaminants into the mineral phase.

Use of Sewage Sludge on Agricultural Lands

A large fraction of the sewage sludge produced in many regions of the world is used as soil amendments often after treatment to reduce the content of harmful microorganisms. Sewage sludge is the semi-solid residue from municipal wastewater treatment plants. Sewage sludge contains nutrients and organic matter that can improve soils. They also contain contaminants and pathogens that are discharged to the sewer system from homes, businesses, industries and streets. Controversy surrounding both the practice of land application and the science behind the regulations as well as allegations of illness and even death resulting from use of sewage sludge prompted the US Environmental Protection Agency to commission a study by the National Research Council (NRC) of the US National Academy of Sciences on the health risks of sewage sludge. The NRC completed its report in 2002 (National Research Council, 2002).

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 arsenic, lead, mercury, cadmium, etc. 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. The radon can diffuse from soil into the air of buildings or into ground water, with resulting radiation exposures to human and animal populations. Other possible sources of contamination internal to soil itself are biological organisms, which are either themselves health threatening or which produce toxic chemicals.

TRANSPORT AND TRANSFORMATION OF SOIL CONTAMINANTS

There are a number of competing processes that impact the fate of a physical, chemical, or biological contaminant found in soils. When a contaminant is added to or formed in a soil column, there are a number of mechanisms by which it can be transported out of the soil column to other part of the environment, be destroyed, or be transformed into some other species.

Therefore, once a contaminant has been identified in the soil column, one must also 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 (i.e., by hydrolysis, oxidation, etc.), or (4) be transported to another part of the environment through a cross-media transfer (i.e., volatilization, runoff, ground water infiltration, etc.). The purpose of this section is to provide an overview of the processes by which contaminants are transported in and out of soil layers and to provide a summary of typical transformation processes. Table 1 summarizes processes by which contaminants are transferred to and from soils.

<Call out to Table 1>

The Composition of Soil

In terms of their ability to transport, sequester, or transform harmful substances, we regard soils as composed of three major phases—gases, liquids, and solids. The fraction by volume that each of these phases contributes to total soil volume varies with soil type and with depth. The volume fraction of soil that is gas varies from a value of 10% typical in clay soils to 25% typical in sandy soils. The volume fraction of gas in soil decreases as one moves from the *A* down through the *C* horizon. The water-phase of soil, the "soil solution" consists mostly of water but includes dissolved minerals and nutrients. The volume fraction of soil that is liquid ranges from 10% typical of sandy soils to 40% typical of clay soils. The solid phase of soil makes up from 50 to 80% by volume of the soil composition and from 75 to 90% by mass of the soil. Soil solids include mineral (i.e. the parent rock) and organic components, including humic acids and decaying matter. The mineral component of soil is in the range of 70 to 90% by mass. The organic phase of soil is defined by the organic-carbon content of the soil. The organic-carbon content of soil ranges from much less than 1% by mass for desert and/or sandy soils to as much as 5% by mass for clay soils and even as high as 10% by mass for carbon rich soils such as peat bogs.

Transport Processes in the Soil Column

In order to understand how chemical species are transported in soil, it is important to recognized that the soil column needs to be viewed as having a least three distinct reservoirs for contaminants. These reservoirs are—(1) the surface-soil layer, (2) the rooting zone, and the (3) deeper unsaturated zone. The nature of these soil components is described below. These layers are illustrated in Figure 1.

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 in the range 0.1 to 1 cm. The ground-surface-soil layer is at the top of the *A* soil horizon. The ground-surface-soil layer has a lower water content and higher gas content than underlying layers. Contaminants in this surface-soil layer are more likely than deeper-soil contaminants to be transported horizontally by mechanical runoff and soil-solution runoff to nearby surface waters. Surface-soil contaminants are susceptible to wind erosion, volatilization, photolysis, biodegradation, and transfer to plant surfaces by rainsplash. In contrast to contaminants in deeper soil, surface soil contaminants are susceptible to chemical transformation by sunlight. Surface-soil contaminants are transferred to and from air by diffusion and resuspension/deposition and transferred to and from the rooting-zone soil by diffusion and leaching.

The Rooting-Zone Soil. Root-zone soil includes the *A* horizon below the surface layer. The roots of most plants are confined within the first meter of soil depth. In agricultural lands, the depth of plowing is 15 to 25 cm. In addition, the diffusion depth, which is the depth below which a contaminant is unlikely to escape by diffusion, is on the order of a meter or less for all but the most volatile contaminants. Soil-water content in the root zone is somewhat higher than that in surface soils. The presence of clay in this layer serves to retain water. Contaminants in root-zone soil are transported upward by diffusion, volatilization, root uptake, and capillary motion of water; transported downward by diffusion and leaching; and transformed chemically primarily by biodegradation or hydrolysis.

The Deeper Unsaturated Soil. The deeper unsaturated soil includes the soil layers below the root zone and above the saturated zone, where all pore spaces are filled with water. This compartment can encompass both the *B* and the *C* soil horizons. The soil in this layer typically has a lower organic carbon content and lower porosity than the root-zone soil. Contaminants in this layer move downward to the ground-water zone primarily by capillary motion of water and leaching. Chemical transformation in this layer is 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, and oxidation/reduction; and biological processes such as microbial transformations. All of these processes can significantly reduce the concentration of a substance or alter its structure in such a way as to enhance or diminish its toxicity.

Radioactive decay. Radioactive elements are made up of atoms whose 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. Most organic contaminants are capable of undergoing photolytic decomposition. Such decompositions can be partial, resulting in the formation of stable byproducts, or complete, resulting in the destruction of the compound or organism. Although the atmosphere attenuates solar radiation before it reaches the earth's surface, the solar radiation generally sufficient to break bonds in many compounds at this surface. Photo-transformation in soil impacts only those contaminants on the soil surface. However, in agricultural lands that are tilled, contaminants in the tilling horizon, (~15-20 cm) can be brought to the surface where photo-transformation occurs. Photo-transformations 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.

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), which can be rapidly altered (e.g., minutes to days) in the presence of water. For amides and carbamates, hydrolytic cleavage yields aromatic and aliphatic amines with increased likelihood toxic activity. Conversely, hydrolytic degradation of compounds that contain stable constituents (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.

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 its oxidation potential (E^O), 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 (pE), which is a measure of electron activity. Redox potentials are relatively high and positive in oxidized environments (e.g., surface waters), and low and negative in reduced environments (e.g., aquatic sediments and 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. Due to their broad range of enzymatic capabilities, microorganisms are capable destroying other microorganisms and transforming many inorganic and organic compounds . The chemical transformations can result in the partial degradation of a compound (e.g., conversion of trinitro-toluene to dinitro-toluene), mineralization (i.e., complete transformation to carbon dioxide and water), or synthesis of a stable product (e.g., formation of methyl arsenicals from arsenate). While these processes generally result in the detoxification of the parent compound, toxic products may also be formed. For example, the microbial metabolism of aromatic amines can result in the formation of toxic byproducts.

HUMAN CONTACT WITH SOIL

Human contacts with soil can be multiple and complex. Table 2 lists a matrix of potential human contacts with soils than can result in human uptake of soil contaminants through inhalation, ingestion, and dermal exposure routes. In the sections below we consider what is known about some of these exposure pathways and how they might be assessed in a risk assessment or other health-effects study.

<Call out to Table 2>

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 contact and ingest soil through their repeated exploration and contact with surfaces and their frequent hand-to-mouth activities. But even adults through activities such as gardening, outdoor labor, and cleaning, are also subject to inadvertent soil ingestion. Some individuals have been observed to intentionally ingest rather large quantities of soil. The ingestion of non-food substances such as soil is called pica. Geophagia is the intentional, chronic, and often addictive consumption of earth. Although they are not activities common to the population at large, pica and geophagia can result in very large consumptions of soil contaminants and put the groups who engage in these activities at much higher risk of exposure to soil contaminants.

Several studies have been conducted to characterize ranges of soil ingestion by children. Some studies make use of measurements of soil levels on children's hands in combination with observations of hand-to-mouth activity to estimate soil uptake. The reliability of this method has improved recently by the introduction of videotaping combined with computer-based evaluation of the tapes to record hand-to-mouth activity. Another approach to soil ingestion measurement makes use of tracer elements in feces. Both feces of children and soil in their play yard are analyzed for elements such as aluminum, silicon, and titanium—elements thought to be poorly absorbed in the gut. Assuming no non-soil 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 are often used as control groups.

Transfer of Soil Contaminants to Vegetation and Food Products

Soil contaminants in both the rooting zone and the surface-soil layer can be transferred to edible parts of vegetation by a number of processes. Contaminants in the rooting zone are transferred to plants through root-uptake. The partitioning of contaminants between soil and root tends to increase with increasing contaminant concentration, since the root-membrane on most plants restricts uptake to dissolved 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. Contaminants in surface soil can be transferred to edible plant parts through resuspension/deposition, rainsplash, and volatilization/partitioning. Resuspension/deposition is the process in which soil particles are blow by the wind up from the soil surface and then fall back onto the leaves of vegetation where the soil contaminants can be retained for some time on the leave surfaces or absorbed by the plant into the leave tissues and possibly transported to other parts of the plant. Rainsplash is a process in which the impact of falling rain drops onto the soil surface causes soil particles to scattered into the air with impact onto plant surfaces. Volatilization/partitioning is a two-step process in which contaminants with a sufficiently high vapor pressure volatilized from the soil and then collect into the waxy surface or the water portion of leaves through air/lipid or air/water exchange.

In the current scientific literature, plant/soil bioconcentration ratios are used to express a concentration ratio that relates the concentration measured in edible vegetation to a concentration in the soil supporting that vegetation. The plant-soil bioconcentration ratio (BCR) expresses the ratio of contaminant concentration in plant tissues, roots, stems, leaves, seeds, and fruit, in mg/kg(plant fresh mass) to concentration in soil. There are different protocols for expressing soil concentration among the different researchers who have measured plant-soil BCR. Some express soil concentration in the soil solution, mg/L, whereas others use the soil dry mass concentration mg/kg.

Contaminants in vegetation can be transferred to food products that are derived from the vegetation. The level of contamination of 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, i.e. the fruit or seeds. In addition, ingestion of contaminated soil and the ingestion of soil-contaminated pasture or grains by food producing animals can lead to the contamination of animal-based food products, that is 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 recreation outdoors. Adults who work outdoors in activities such as construction, farming, or gardening can have rather high soil loadings on their skin. Children playing outdoors also can have rather large soil loadings 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 dermal contact with a contaminated soil involves a number often difficult-to-measure parameters, 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, i.e. days per year, that an individual is involved in an activity the results in soil contact. The exposure time is a measure of how long, in hours, the soil is in contact with skin during and exposure activity.

Dose estimates for soil contact include a great deal of uncertainty. This uncertainty arises because we must deal with 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 addressing 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. The inhalation of suspended particles can take place both outdoors and inside buildings. Exposure assessors and toxicologists now recognize that fine and coarse particles in the indoor environment are attributable to both air and soil sources and enter the indoor environment by processes such as penetration through windows and cracks 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 as well as on the feet and fur of pets.

Contaminant Vapor Transport into Buildings

The vapors 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. These are (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.

Ground Water Contamination

Soil contaminants can be transformed by physical, chemical, and/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 ground water these contaminants can contact humans through a number of exposure pathways—such direct water ingestion, dermal uptake in showers/baths, irrigation of crops, feeding food-producing animals, etc.

SUMMARY

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, and the types of human activities that could result in human exposure to soil contaminants. 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 and indirect soil contact. Toxicologists should be aware of the complex nature of soils, of the potential of soil contamination, and of types of direct and indirect contacts that human populations have with soil.

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

Gains	Losses
deposition from air	volatilization to air
washout from air by rainfall	resuspension of soil particles
dry deposition of air particles	mass transfer (diffusion and advection) downward to ground water
mass transfer (diffusion and advection) upward from ground water	transfers to vegetation
contaminant sources	soil solution runoff
	erosion (mineral runoff) to surface water
	chemical/physical transformation

Table 2. The matrix of exposure pathways the 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 ground water contaminated by soil
Inhalation	•Inhalation of soil vapors that migrate to indoor air •Inhalation of soil particles transferred to indoor air
Dermal contact	•Dermal contact with soil

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