Review Paper

SOIL INGESTION BY HUMANS: A REVIEW OF HISTORY, DATA, AND ETIOLOGY WITH APPLICATION TO RISK ASSESSMENT OF RADIOACTIVELY CONTAMINATED SOIL

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Abstract—**Ingestion of soil by humans has been a documented phenomenon for centuries and still takes place today according to various literature. The literature reviewed here shows that there are two distinct soil ingestion phenomenon: inadvertent and purposeful (geophagia). Certain lifestyles, occupations, and living conditions will likely put different individuals or different groups at risk to these separate, but sometimes related, phenomenon. In particular, reports of geophagia are relatively common for the life stages of adolescence and periods of growth, and during pregnancy and lactation. Geophagia also appears to be relatively common among indigenous peoples on all continents, sometimes taking place to extreme degrees. Because of their high dependence on the land, indigenous peoples are also at highest risk for inadvertent ingestion. Inadvertent intake is more a function of either primitive living conditions or professions that may bring workers into close and continual contact with the soil. It is the purpose of this report to review and summarize literature related to ingestion of soil by humans with emphasis on the relevance of soil ingestion to radiological dose assessment, the etiology of geophagia and its relationship to risk assessment, qualitative observations and quantitative studies of direct soil ingestion by humans with interpretations useful for different lifestyle scenarios, the status of a number of current radiological assessment models in accounting for soil ingestion, and some unresolved issues in modeling the ingestion of soil.**
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Key words: ingestion; soil; risk analysis; environmental transport

INTRODUCTION

In recent years, risk assessments for environmental exposures have moved from generally conservative point estimate calculations to calculations that attempt realism and account for the attendant uncertainties. In highly conservative calculations, minor pathways of exposure are sometimes ignored, as they are considered to be accounted for implicitly. In more realistic calculations, however, numerous minor exposure pathways need to be considered. Depending on the exposure scenario and the radionuclides involved, these minor pathways may include inhalation, ingestion of vegetables (surficial and interior contamination), water, soil, and contamination of skin and wounds. The focus of this paper is an examination of soil ingestion, relevant literature data, and an analysis of related factors.

This report reviews much of the available literature on soil ingestion; that body of information has reported a variety of types of data including narrative descriptions, qualitative observations, quantitative studies of soil ingestion, estimates of intake based on a variety of assumptions and indirect measurements, and summaries of others' works. The objective of reviewing literature on soil intake from various countries and ethnic populations is to determine both the likelihood (i.e., frequency and probability) of its occurrence within those groups and to estimate soil ingestion-rates suitable for risk assessment in a wide variety of settings. For dose or risk assessments, it is preferable to have empirical and validated data describing the variability of intake among members of the particular group of interest. Such information is needed to determine the distribution of possible dose commitments and/or risks. Although this ambition exceeds the database available presently, there is no paucity of published reports confirming the occurrence of both inadvertent and intentional soil ingestion in a variety of environmental and cultural settings. The main purpose of this paper is to present a review of available information on soil ingestion with an emphasis on application for radiation risk assessment and secondarily to discuss the specificity of available literature data to certain population groups. To the degree that the literature can be generalized, a set of soil ingestion parameters for nine different lifestyle scenarios is presented here. These values may be found useful for risk assessment purposes if it is determined that the scenario description is appropriate to the assessment under consideration.

An increased awareness of soil ingestion as a pathway of exposure came about from the development of the field of hazardous chemical waste risk assessment (NRC 1980, 1991; EPA 1989a, b, c; EPA 1990a; ATSDR 1992). Development of that field has evolved primarily

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as a result of national legislation (e.g., the Comprehensive Environmental Response, Compensation and Liability Act of 1980 or "Superfund") and research programs by the Environmental Protection Agency (EPA). It is not altogether clear whether the importance of soil ingestion is greater for hazardous chemical risk assessment or radiological risk assessment. However, one purpose of this review is to provide an examination of published data such that future radiological assessments can make a qualified determination of the importance of the soil ingestion pathway to their particular situation.

The phenomenon of soil ingestion has been discussed in the literature usually as an anthropological oddity or with various clinical and public health endpoints in mind. In particular, the phenomenon has been examined for children. It is well known that young children are particularly susceptible to direct intake of soil-borne substances whether it be pesticides, bacteria, or radioactivity. During infant years, children normally exhibit mouthing behavior whereby their hands are repeatedly moved in and out of their mouth during the day; in some cases, young children and even adults intentionally ingest soil. Considerable attention has also been drawn to the apparent correlations between soil intake, anemia, and pregnancy. Most literature that has reported on the public health concerns of soil ingestion have been focused on the health implications that arise due to the intake (via soil) of a variety of environmental toxins including lead (de la Burde and Reames 1972; Shellshear 1973; Barltrop et al. 1974; Vostal et al. 1974; Shellshear et al. 1975; Wedeen et al. 1978; Charney et al. 1980; Wilson et al. 1986), copper (Holt et al. 1980; Cheek et al. 1981), potassium (an excess causing hyperkalemia) (Gelfand et al. 1975), diesel fuel (Millner et al. 1992), animal fecal toxins which cause toxoplasmosis (Stagno et al. 1980; Frenkel and Ruiz 1981), roundworm (*Toxocara canis*) from dogs (Marmor et al. 1987; Wong et al. 1988) or other parasites (Lanzkowsky 1959; Holt et al. 1980), DDT (Lowe and Jamall 1994), and TCDD (Kimbrough et al. 1984; Finley and Paustenbach 1994). In addition, public health interests include recognizing and ameliorating intestinal damage from puncture or impaction due to excessive soil consumption (Vessal et al. 1975; Bateson and Lebroy 1978; Key et al. 1981; Hawass et al. 1987; Wrenn 1989), skeletal fluorosis (fluoride poisoning) (Fisher et al. 1981), anemia (Say et al. 1969; Cavdar and Arcasoy 1972; Ronaghy and Halsted 1975; Arcasoy et al. 1978; Cavdar et al. 1983; Prasad et al. 1983), or pregnancy complications (Reid 1992). The majority of public health related literature on the subject of soil ingestion has focused on the phenomenon of intentional rather than inadvertent soil ingestion because those cases generally have higher morbidity rates and more severe clinical endpoints.

The soil ingestion pathway, though discussed in various contexts, has not been comprehensively evaluated in the open literature for radiation risk assessment purposes. Some previous reports which have recommended limits for actinide contamination of soil (e.g., Healy 1974; EPA 1990b) have briefly discussed the pathway. The absence of a comprehensive examination of this subject with respect to sex, age, environment type, socioeconomic status, and ethnicity is evidenced by the deficiency of appropriate data from which ingestion-rate and other related modeling parameter values can be derived for different age groups and specific occupations, lifestyles, environments or different ethnic/cultural groups. The phenomenon of intentional soil ingestion is shown in this review to be very strongly related to lifestyle attributes and practices of certain cultural/ethnic groups and to particular environmental settings. In contrast, those people with occupations that bring them into frequent contact with the soil are also at higher risk for inadvertent ingestion of soil.

The circumstances of soil ingestion are divided here into those in which soil is ingested (1) inadvertently by swallowing dirt or dust (e.g., accompanying mouth breathing), via food items contaminated with soil, from mouthing of dirty hands or other contaminated non-food items, or (2) intentionally, i.e., deliberate consumption of clay, soil, or any earthen materials. It is the general purpose of this paper to provide information useful for gaining an understanding of soil ingestion with particular application to dose assessment from radioactively contaminated soil.

BACKGROUND

Definitions

The concepts of soil and ingestion are normally taken for granted as self-explanatory. However, brief definitions are provided so as to create a single concept for discussion purposes. Soil can be viewed simply as a mixture of inorganic and organic solids, air, water and microorganisms (Bohn et al. 1985) or "a collection of natural bodies which has been synthesized in profile form from a variable mixture of broken and weathered minerals and decaying matter, which covers the earth in a thin layer, and which supplies, when containing the proper amounts of air and water, mechanical support and sustenance for plants" (Brady 1974).

Ingestion implies the process of taking material into the gastrointestinal tract (Thomas 1993). Because some soil is resident in the air as fine dust and because some individuals are mouth-breathers, inhalation of dirt can sometimes be followed by swallowing of dust particles. The requirement that the material enter the gastrointestinal tract to be defined as ingestion is an important distinction because there is an interdependence of the amount of soil inhaled through the nose and through the mouth. The distinction between ingestion and inhalation must be made so as not to distort the relative importance of either pathway of exposure (Zach and Barnard 1987; Layton 1993).

The phenomenon of purposeful soil ingestion has received its own terminology. Taber's Medical Dictionary (Thomas 1993) defined pica to be "An eating disorder manifested by a craving to ingest any material

not fit for food, including... clay... ". Lanzkowsky (1959) also defined pica to be a perversion of appetite with persistent and purposeful ingestion of unsuitable substances (also see Danford 1982). Geophagia is more specific and was defined to be: "A condition in which the patient eats inedible substances, as chalk, clay or earth" (Thomas 1993). There are at least nine different "phagias" or types of pica (Lacey 1990), each with a specific substance which is consumed obsessively. Of those, only clay and soil phagias are discussed here.

Numerous authors have given variants of the above definitions of geophagia in the course of reporting their observations. Most agree with Reid (1992) that geophagia or earth eating is a special case of pica. Halsted (1968) defined geophagia as the habit of eating earth including clay and other types of soil, whereas pica means the eating of any foreign substance and thus includes eating of soil. Barltrop et al. (1974) defined soil pica subjects to be those children who habitually put fingers or toys in their mouths while playing in their gardens as well as putting soil directly in their mouths and included children who had pica for other substances in addition to soil. Calabrese et al. (1991) defined soil-pica as ingestion of soil in amounts far exceeding those observed in the average child. This discussion will use the term "inadvertent ingestion" and "geophagia" to distinguish between accidental and intentional ingestion.

Rationale for considering soil intake in radiological assessments

Soil contains the largest inventory of radioactivity of any part of the natural terrestrial surface environment. Most of the radioactivity in the terrestrial environment that is either natural in origin or that has been dispersed from accidents or intentional releases is either bound to, or resident in, the components of the soil. Of this inventory, a fraction can be transferred from the soil surface to surfaces of vegetation via resuspension and deposition or rain-splash, or from the root-zone layer of the soil to the interior of plants via root uptake. For purposes of radiation risk assessment, all pathways of exposure that originate with contaminated soil may be potentially important although only the direct intake of soil into the gastrointestinal tract is considered here. Within this definition, ingestion of soil could either take place in the absence of foods or as a contaminant on the surface of unwashed foods.

The incidence of both inadvertent and intentional consumption of soil is apparently world-wide in distribution as well as occurring at all ages (Lanzkowsky 1959; Halsted 1968; Reid 1992). Geophagia can be traced as far back as 1000 A.D. according to Halsted (1968) and has been documented for centuries (Cooper 1957; Danford 1982). Furthermore, geophagia and other forms of pica have been reported in numerous cultural and ethnic groups and subpopulations, particularly among children and pregnant women, as well as the socially disadvantaged, groups of low income and socio-economic status, developmentally delayed persons, and the mentally retarded (McAlpine and Singh 1986). It is worthwhile to note the variety of countries and environmental settings that have reported observations of geophagia, many of which are summarized in this review (see Tables 1, 2, and 3). The extensively documented incidence of soil ingestion over time, geographic, ethnic and cultural boundaries is justification for examining its relevance to radiation risk assessments.

Inadvertent soil ingestion: verification and causes

Soil ingestion, whether inadvertent or intentional, is difficult to verify and quantify. In particular, inadvertent intake is by definition accidental and likely not to be observed or recognized. Inadvertent ingestion can take place, for example, in dusty environments where inhalation of dirt is likely as a result of wind-driven resuspension. In that case, it can be assumed that swallowing will lead to the ingestion of soil.

Inadvertent soil ingestion can only be observed and, hence, verified under unusual circumstances. Observing accidental phenomena requires observations that do not disturb those being observed, and such studies are difficult to conduct. To a limited degree, it is possible to watch the habits of children playing outdoors or make observations of adults involved in construction, agriculture, food gathering or during high wind and resuspension incidences. However, such observations rarely, if ever, provide quantitative estimates of use for estimating ingestion. Most experimental studies of resuspension, such as have been conducted in the Marshall Islands (Shinn et al. 1997), have been examined mainly in light of estimating exposure via inhalation.

Most literature that has recommended values of inadvertent intake for risk assessment purposes has made those estimates based on assumptions. These suppositions have included extrapolation from meager data or, in some cases, guessing or assuming the number of times children might put candy that has collected surface dirt or dirty hands in their mouths.

The most reliable estimates of inadvertent soil intake are from studies that have inferred their findings from the quantity of soil trace elements measured in feces (Binder et al. 1986; Linsalata and Eisenbud 1986; Clausing et al. 1987; Calabrese et al. 1989; Davis et al. 1990; van Wijnen et al. 1990). The more careful of these studies attempt to subtract the amount of trace elements ingested from non-soil sources. The need to consider non-soil sources of natural tracer elements is exemplified by titanium, which is not only a common tracer for soil contamination, but also may be inadvertently ingested during the use of commercial toothpaste.

Inadvertent soil ingestion is enhanced by the same conditions that encourage inhalation of dust: dry, dusty climates, dusty dwellings, open air dwellings, primitive or dry living conditions in which little access to washing of foods and the body is possible, living conditions in which children may play on the floor, and occupations that involve direct contact with soil or moving soil by mechanized means (ATSDR 1992). Various empirical

Table I. Selected literature reporting worldwide observations (qualitative studies) of geophagia.

Author	Publication date	Population that exhibited geophagia/specifics of instances
Hooper and Mann	1906	India—children and pregnant women
Christopherson and Cantab	1910	Egyptian Sudan, medicinal uses of earth ingestion (including treatment of syphilis and anemia)
Laufer	1930	Observed on every continent, consumption for religious and magical purposes, consumption by pregnant and lactating women, consumed as famine food or as a regular part of some diets; Native Americans of the U.S. Southwest—eat clay with bitter raw potatoes; Native Americans in southern California—bake bread with clay and corn
Whiting	1947	North Carolina, red and white clay consumed during pregnancy
Cooper	1957	6th century Roman writings—observed among some men, women and children, during pregnancy was the most common, also among Indian groups in South America along the Orinoco River
Anell and Lagercrantz	1958	Extensive anthropological observations of geophagia in Indonesia, Oceania, Africa and among blacks of North America
Clayton	1965	Fifty black informants in Alabama, clay consumed by children and child-bearing women
Vermeer	1966	Nigeria—all pregnant women of the Tiv Tribe, traditional medicinal preparation for diarrhea, gastric irritation associated with intestinal parasitic diseases
Green and Jones	1968	Zapotec Indians in Oaxaca, Mexico, manufactured panecitos banditos, tablets of clay for medicinal purposes, formed in shapes of religious images
Vermeer	1971	Ghana—children and adults for gastric relief, mineral supplement during pregnancy
Hunter	1973	Ghana—children and adults for gastric relief, mineral supplement during pregnancy
Taylor	1979	South Texas community, clay consumed during pregnancy
Hunter and de Kleine	1984	Black Carib women in Belize, medicinal tablets from clay
Vermeer and Farrell Jr.	1985	Nigerian village of Uzalla, traditional West African medicine during pregnancy and for stomach ailments and dysentery
Hawass et al.	1987	Report of three cases of geophagia in Saudia Arabia, two with a history of eating mud, a third of eating pebbles

data are in agreement with the qualitative statements of ATSDR. For example, data from the Marshall Islands resuspension studies (Shinn et al. 1997) show an enhancement of the concentration of radioactivity in the air relative to that in the soil (Bq per gram in the air/Bq per gram in soil) during outdoor work that involved digging or using tools on the ground (enhancement of 2.6×) and in work situations in and around houses (primitive type).

Geophagia: etiology and relationships with other factors

Because inadvertent soil ingestion does not qualify as a disease, it has no associated etiology. However, because geophagia is considered an aberrant behavior, i.e., a mental disease or compulsion (see Hattis and Burmaster 1994), or can result in damage to the health of individuals, it has an associated etiology. Although the etiology of this habit continues to draw the attention of some medical practitioners, public health specialists, psychologists and anthropologists, the etiology of geophagia is usually not an issue of major importance to estimating dose to individuals exposed to radioactively contaminated soil. Radiation dose to identified individuals is normally assumed to be a function of their body size, the total intake of radioactivity, and their personal biokinetics, if they were known. However, for risk evaluations to populations or to representative (unidentified) individuals, the etiology of geophagia is relevant to estimating the likelihood of geophagia occurring in the specific cultural setting under consideration. Current knowledge of geophagia does not yet allow precisely predicting the prevalence of geophagia in specific cultures or socioeconomic settings, though an understanding of those factors that appear to be causal should be useful for estimating its likelihood within cultures of various levels of economic development.

Lanzkowsky (1959) discussed the etiology and treatment of soil pica and concluded that iron deficiency is the major cause of soil pica and that iron therapy is curative (also see Carlander 1959). This theory dominated the medical publications on geophagia before 1970, most of which were reports of clinical observations. Some controlled studies (e.g., Gutelius et al. 1962; Gutelius et al. 1963), however, found that neither mineral supplements or placebos were effective in eliminating the habit of pica. Ansell and Wheby (1972) reviewed the medical literature in detail; the conclusions that seem to emerge from numerous publications is that anemia is sometimes, but not consistently, found to be associated with geophagia. In some populations, geophagia may be common in groups at greatest risk for anemia, e.g., poorly nourished, pregnant women. Thus, the association seems to be statistical rather than casual.

Table 2. Selected literature reporting the incidence or frequency of geophagia.

Author	Publication date	Study population/Incidence of geophagia
Berkel et al.	1970	21 patients between 3.5 and 16 y with multiple symptoms including geophagia and iron-deficiency anemia. Soil pica lasted from 6 mo to 13 y
Cited by Bruhn and Pangborn (1971):		
Dickins and Ford	1942	25% of 209 Negro children between 7 and 13 y engaged in pica within the preceding 10 to 16 d
Hertz	1947	"Many" cases of clay-eating among pregnant black women in North Carolina
Ferguson and Keaton	1950	27% of 331 pregnant black women ate clay, 7% of 30 white women
Cooper	1957	Reported a pica prevalence rate of 27.2% in a sample of 386 black children up to 6 y and prevalence rate of 16.8% in similar sized sample of white children
Bradley and Bessman	1958	69.6% of 333 children in low-income area of Baltimore exhibited pica
Millican et al.	1962	32.3% of 486 black children in clinics were ingesting non-edible substances, 10% of 294 white children with same behavior
Bruhn and Pangborn	1971	32% of 65 migrant Mexican families and 54% of 26 migrant Anglo families said their children exhibited pica; 38% of pregnant women in 65 migrant Mexican families and 19% of pregnant women in 26 migrant Anglo families mentioned their pica practice in a questionnaire (dirt was the predominant item consumed by children while dirt, cigarette ashes, bean clods, clay pots and laundry starch were consumed by women)
Cavdar and Arcasoy	1972	20 village Turkish children (9 female, 11 male), ages 3 to 17 y identified with long standing pica associated with anemia (duration of pica was from 1 to 15 y, 17 of cases were soil pica, 2 with clay pica and 1 with plaster pica).
Arcasoy et al.	1978	12 Turkish children (6 male, 6 female) with prolonged geophagia (lasting 5 to 15 y), 4 males and 4 females between 4 and 7 y of age, 2 females 8 y old, and one male 12 y and one male 15 y of age
Bateson and Lebroy	1978	11 Australian aboriginal patients exhibited opaque masses of clay in the colon upon diagnostic radiological examination. The eating of white clay was determined to be mainly for medical purposes or to allay hunger and not related to anemia or pregnancy. The observed behavior resulted in severe complications for 5 of the 11 individuals.
Cited by Cavdar and Arcasoy (1972):		
Tayanc	1943	Syndrome characterized by geophagia, iron deficiency and other conditions described in Turkish literature
Prasad et al.	1961	Geophagia syndrome in Iran occurred exclusively in males, associated with zinc deficiency
Holt et al.	1980	364 persons in two aboriginal communities in Australia (tropical northwest), ages 5–77 y were studied for serum trace levels; depressed zinc and iron levels were found consistent with geophagia
Key et al.	1981	One of few maternal deaths reported from complications of geophagia is reported, 31-y-old black female reported eating 200–300 g each day during two pregnancies
Cheek et al.	1981	300 aboriginal people in Australia studied, 5–70 y of age, geophagia was reported to be common, reported to result in zinc deficiency (causing growth stunting) and copper toxicity.
Fisher et al.	1981	A 40-y-old American Indian woman in AZ reported craving soil for past 20 y since 3rd pregnancy, more pronounced during past 3 y, typically ingested 50 g d^{-1} resulting in skeletal fluorosis; noted geophagia to be widespread among certain southwestern American Indian tribes who also have renal impairment
Lanzkowsky	1959	Five-month study of 12 children in Red Cross Hospital in Cape Town, South Africa, who exhibited pica
McAlpine and Singh	1986	56 mentally retarded children (9.2%) of 607 were observed to engage in pica
Barltrop et al.	1974	119 children studied in U.K. aged 2–3 y, 43% put fingers, toys and soil in their mouths while playing, 9% were known by mothers to have ever swallowed soil.
Cited by McAlpine and Singh (1986):		
Sharma et al.	1978	Pica prevalence rate of 47.1% in a sample of 350 Indian children of ages 1 to 5 y
National Research Council	1976	Reported that approximately 50% of all American children between 1 and 3 y of age engage in pica
Say et al.	1969	45 cases of iron-deficiency anemia associated with geophagia were studied in Turkey
Shellshear	1973	Lead poisoning in a 20-mo child with pica, concluded that child had been eating soil for at least 12 mo
Shellshear et al.	1975	Pica prevalence rate of 14% in a sample of 136 white children of ages 1 to 5 y
Horner et al.	1991	Pica affects at least 20% of high-risk pregnant women—most likely black, living in rural areas and having a family history of pica: prevalence odds reported during pregnancy: 0.52 for blacks and 0.12 for whites; 1.03 rural (both races) and 0.44 urban (both races); 0.54 for southern U.S. and 0.47 for northern U.S.
Edwards et al.	1994	553 urban pregnant black women (District of Columbia), 0.5% exhibited pica for clay, 0.4% for dirt (while pregnant). As youth, 3.3% engaged in clay pica and 6.2% in dirt pica.

Table 3. Selected literature reporting quantitative estimates of soil ingestion-rate (inadvertent and geophagia), ordered by publication date.

	Rural or urban (R/U)	Child or adult (C/A)	Geophagia or inadvertent ingestion (G/I)	Study summary/Analysis methods	Ingestion-rate estimates			Basis for ingestion-rate estimates (A, E, IM, M, LR)[a]
Lepow (1974)	U	C	I	Measured dirt on hands of 22 children in urban CT, assumed children mouth their hands 10× per day	10× d^{-1} × 10 mg = 100 mg d^{-1}			IM, A
Day et al. (1975)	U	C	I	Dirt measured on sticky candy, ingestion-rate based on assumed 2–20 sweets consumed per day	10–1000 mg d^{-1}			IM, A
Gelfand et al. (1975)	R/U	A	G	Five black patients (33–59 y, 2 male, 3 female) with chronic renal failure were known to have consumed large amounts of clay	frequency	amount (g)	intake (g d^{-1})	E
					2×–3× mo^{-1}	2–800	0.1–80	
					1×–2× mo^{-1}	200	6.6–13.3	
					daily	10–50	10–50	
					1×–2× mo^{-1}	150	5–10	
					1 mo^{-1}	100	3.3	
Martin and Bloom (1975)	R	A	I	Theoretical assessment calculations (desert environment)	8–11 mg d^{-1}			A
Rogers (1975)	R	A	I	Theoretical assessment calculations for mid-west U.S. environment (Mound Laboratory in Ohio)	8–11 mg d^{-1}			A
Duggan and Williams (1977)	?	C	I	Based on soil on hands and observations of mouthing behavior	25 mg d^{-1}			E
Healy (1977)	R	C	G	Theoretical assessment calculations for exposure to transuranic radioactivity	20 g d^{-1}			A
Mahaffey (1977)	U	C	G	Estimate of paint consumption by children with pica	140–340 mg d^{-1}			E
Wedeen et al. (1978)	R/U	A	G	46-y-old black woman with lead poisoning and anemia	2–4 g d^{-1} for 12 y[b]			E
Vermeer and Frate (1979)	R	C/A	G	Nutritional questionnaire to determine consumption of clay	10 to 150 g d^{-1}, average of 50 g d^{-1}			E
National Research Council (1980)	U	C	I	Estimate of ingestion of street dust	40 mg d^{-1}			E
Fisher et al. (1981)	U	A	G	40-y-old American Indian woman, ingestion-rate estimated, confirmed from flouride analysis of bone biopsy	typically 50 g d^{-1}			E, IM
Kimbrough et al. (1984)	U	C/A	I	Theoretical assessment calculations for exposure to TCDD contamination	1 g d^{-1} for children age 9–18 mo, 10 g d^{-1} for 18–42 mo, 1 g d^{-1} for 42 mo to 5 y, 100 mg d^{-1} for > 5 y			E
Hawley (1985)	U	C/A	I	Based on ingestion of soil and dust	165 mg d^{-1} at 2.5 y age, 24 mg d^{-1} at 6 y age, 61 mg d^{-1} for adult			E
Binder et al. (1986)	U	C	I	59 children aged 1–3 y in Montana were studied in summer using fecal analysis for soil trace elements	181 mg d^{-1} (Al) 184 mg d^{-1} (Si) 1834 mg d^{-1} (Ti)			M
Linsalata and Eisenbud (1986)	U	C/A	I	Stool samples collected from 2 farms in Pocos de Calda plateau of Brazil, fecal analysis for thorium	200 mg d^{-1}			M
Clausing et al. (1987)	U	C	I	18 children in nursery schools, fecal analysis for soil trace elements was compared against 6 hospitalized children who did not play outside	50 to 100 mg d^{-1}			M

LaGoy (1987)	not specified	C/A		Compilation of literature	Age	Average to maximum value (mg d^{-1} but no pica)	LR
					0–1 y	50–250	
					1–6 y	100–500	
					6–11 y	50–250	
					>11 y	25–100	
Wong (1988), Wong et al. (1988)	?	C	I/G	Observations made for 4 mo in 2 government supervised homes in Jamaica for children awaiting foster home placement, analysis by fecal sampling for silica	25%, > 100 mg d^{-1} 14% > 200 mg d^{-1} 4% > 300 mg d^{-1} young children, 470 ± 370 mg d^{-1} 10.5% of young children > 1 g d^{-1} 21% > 1 g d^{-1} on at least 1 occasion, intake-rates for single time-geophagia incidences of 3.7 to 61 g d^{-1}		M
Calabrese et al. (1989)	U	C	I/G	65 children, 1–4 y of age in greater Amherst, MA, area, fecal analysis for soil trace elements during 8-d period, one soil pica child identified	9 to 40 mg d^{-1} for non-pica, 5 to 8 g d^{-1} for pica		M
Calabrese et al. (1990)	U	A	I	6 adults studied as part of a validation program in a child soil ingestion study (Calabrese et al. 1989)	approximately 50 mg d^{-1}		M
Davis et al. (1990)	R/U	C	I	104 school children randomly selected, 2–7 y of age in S.E. Washington state, fecal analysis for soil trace elements	39 mg d^{-1} (Al) 82 mg d^{-1} (Si) 245 mg d^{-1} (Ti)		M
EPA (1989a,b,c,1990a)	R/U	C/A	I	Regulatory guidance values	200 mg d^{-1} for children 100 mg d^{-1} for adults		LR, A, E
Haywood and Smith (1990)	R	C/A	I/G	Aboriginal population, considered consumption of soil contaminated water and other sources, estimates based on observation, assumption	10 g d^{-1} for all age groups, noted as unrealistic for 3-mo-old infants		E, A
van Wijnen et al. (1990)	R/U	C	I	Two different groups in summer in the Netherlands were studied and compared to hospitalized children, using fecal analysis for titanium:			M
	U			day care groups	0 to 90 mg d^{-1} (geometric mean)		M
	R			camping groups	30 to 200 mg d^{-1}		M
Calabrese et al. (1991)	U	C	G	One child (3.5 y, female) of 64 (see Calabrese 1989) displayed pica during 2nd week of two week observation period, fecal analysis for soil trace elements	10 to 13 g d^{-1} during 2nd of 2-week observation period		M
Thompson and Burmaster (1991)	U	C	I	Reanalyzed data of Binder et al. (1986) using actual stool weights, fitted parametric (lognormal) distribution	59 mg d^{-1} (geometric mean), 91 mg d^{-1} (arithmetic mean), 126 (standard deviation)[c]		LR
ATSDR (1992)	R/U	C/A	I/G	Regulatory guidance values	50–100 mg d^{-1} for non-geophagic child, 50 mg d^{-1} for adult, 5 to 10 g d^{-1} for geophagic child		LR, A, E
de Silva (1994)	U	C		Used blood levels of lead from Barltrop (1975) and Barltrop et al. (1975) to determine ingestion-rate of lead contaminated soil	4 mg d^{-1}		IM
Finley and Paustenbach (1994)	U	C/A	I	Fitted child data of Calabrese and Stanek (1992) to parametric (lognormal) distribution	Arithmetic mean value of 16 mg d^{-1}, 90 mg d^{-1} standard deviation		LR
	residential			Assumed for a case study of TCDD risk assessment: at 1×10^{-5} risk	0–1.5 y: 0.1–10 mg d^{-1} (uniform distribution) 1.5–5 y: 9–50 mg d^{-1} 6–12 y: 5–50 mg d^{-1} 13–30 y: 0.1–50 mg d^{-1}		A
	construction site				0.1–30 mg d^{-1} outdoors (uniform distribution) 0.1–10 mg d^{-1} indoors		A

continued on next page

11/18/2003 10:30 8654810060 SENES OAK RIDGE PAGE 08/27

Table 3.—*Continued*

Author(s) (publication date)	Rural or urban (R/U)	Child or adult (C/A)	Geophagia or inadvertent ingestion (G/I)	Study summary/Analysis methods	Ingestion-rate estimates	Basis for ingestion-rate estimates (A, E, IM, M, LR)[a]
Lee and Kissel (1995)	U	C	I	Back-calculated from measurements of urinary arsenic using EPA ingestion and inhalation models	median = 84.5 mg d^{-1} mean = 261 mg d^{-1} std. dev. = 625 mg d^{-1} 95th% = 986 mg d^{-1}	IM
Sheppard (1995)	U	C/A	I/G	Recommended values, all geometric mean values	pica child 500 mg d^{-1} (GSD = 12) 2.5 y: 50 mg d^{-1} 6 y: 20 mg d^{-1} adult gardener: 20 mg d^{-1} adult (indoors): 0.4 mg d^{-1}	LR
Stanek and Calabrese (1995)	U	C	I/G	Revision of estimates presented in Calabrese et al. (1989)	Range of median soil ingestion of 64 subjects over 365 d: 1–103 mg d^{-1}. Range of average daily soil ingestion for 63 subjects over 365 d: 1–2268 mg d^{-1}. Median of the daily average soil ingestion for 64 subjects: 75 mg d^{-1}. Range of upper 95% soil ingestion estimates: 1–5263 mg d^{-1} Median upper 95% soil ingestion estimate of 64 subjects over 365 d: 252 mg d^{-1}.	M

[a] Basis for ingestion-rate estimates; Assumption (A), Estimate (E), Indirect measurements (IM), Direct measurements (M), Literature review (LR).
[b] Derived by this author from lead ingestion-rates reported by Wedeen et al. (1978).
[c] Equivalent to a geometric mean (GM) of 59 mg d^{-1} and geometric standard deviation (GSD) of 2.8.

Halsted (1968) commented that nearly all authors reporting on geophagia regard it as especially common in pregnancy, but that it also occurs in both sexes and at all ages up to 80 y. The etiology apparently has many sources including a means of producing satiety in populations where hunger is widespread (Edwards et al. 1994) and to satisfy cravings. Although authors have reported that geophagia was a physiologic response to a nutritional need for basic elements, most present day investigators have discounted this theory. One confounding factor that has helped propagate this theory is that geophagia often leads to, rather than corrects, iron or zinc deficiency. This phenomenon is particularly acute where clay with a high cation-exchange capacity is ingested.

Some of the factors suspected of being involved in the etiology of soil pica were divided by Mitchell et al. (1977b) into physiological and psychological factors. These are discussed separately in the following sections.

Physiological factors

Some of what is known about the physiological etiology of geophagia is a result of animal studies, and these may have only limited relevance to human behavior. For example, Mitchell et al. (1976) concluded from rat studies that pica is an "illness-response" behavior and is analogous to vomiting in other species. The phenomenon, therefore, may be a response to mitigate the effects of toxic agents that have been introduced into the body. Mitchell et al. (1977a) also reported that pica in rats was a response to motion sickness. The work of Mitchell indicated that pica in rats can be a behavior response to illness and may persist after the cessation of the physiological cause. Therefore, pica may in some instances be the expression of a conditioned response learned from periods of physiological stress.

In studies similar to Mitchell, Burchfield et al. (1977) reported studies on rats that indicated that geophagia increased when rats were made acutely ill. They concluded that geophagia "may occur in response to any homeostatic alteration (stress state)". In particular, the authors noted that geophagia occurred in response to the induction of arthritis and as a response to acute gastrointestinal illness.

There are also examples whereby animals have been shown to attempt to maintain bodily homeostasis by consuming extra sodium (Botkin et al. 1973) or phosphorus- or calcium-rich foods (Denton et al. 1986) if these items were withheld or not available from their diet in their normal form. These examples account for animals eating bones and certain aquatic plants in large volumes. Schmidt-Nielsen (1994) discussed that mechanisms of the body to maintain internal steady states are poorly, if at all, understood, yet he acknowledges that in the cases of sodium and phosphate deficiency, an animal's behavior serves to correct an imbalance or deficiency (also noted by Johns and Duquette 1991, who cite Rozin 1976). It is not known whether geophagia in humans is rooted similarly to the phenomena in which animals behaviorally attempt to correct nutrient deficien-

cies. Johns and Duquette (1991) note that while animal behaviorists look for adaptive functions that geophagia may satisfy, human nutritionists consider geophagia as a symptom of metabolic dysfunction or aberrant behavior. Neither theory can yet be confirmed for humans.

Psychological and cultural factors

Examples of psychological factors that have been implicated with geophagia include mental retardation (Kanner 1948), habit (Halsted 1968), emotional neglect (Cooper 1957), persistence of an infantile hand-mouth behavior (Robischon 1971) and cultural tradition (Vermeer 1966; Vermeer and Frate 1979).

Although geophagia in the U.S. is typically associated with urban and/or poor living conditions in the southern part of the country, a noticeable incidence of geophagia was documented as late as 1970 in New York City (Roselle 1970 cited by Gelfand et al. 1975). Crosby (1976) and Wedeen et al. (1978) also note that the cultural tradition of eating clay has recently been transplanted to northern metropolitan areas and is not limited by socioeconomic or racial background.

Although geophagia is associated with poverty groups in industrialized nations, this is not necessarily the case for less well developed countries. For example, Halsted (1970) reports that clay to be ingested is commonly sold in markets in Ghana and that clay squares for consumption, imprinted with a cathedral, are sold in Guatemala, usually to pregnant women. Johns and Duquette (1991) noted that in many traditional subsistence societies, deliberate consumption of earthen substances is a normal behavior.

Geophagia is sometimes associated with more primitive societies. For example, geophagia among Australian aboriginals was discussed by Bateson and Lebroy (1978). They reported on 11 cases of soil pica, which were examples of extreme consumption of white clay, often resulting in colon blockage or sometimes perforation. The clay is apparently ingested purposely, first being rolled into small balls. The purpose of the clay ingestion is believed to be to cure stomach aches and diarrhea or to prevent poisoning from some fish. In addition, clay is eaten by the aboriginals to allay hunger or to treat hookworm infestation. Finally, clay is ingested sometimes during celebrations when it is used as a pigment for body painting.

The human population of greatest concern is pregnant women. Edwards et al. (1994) discussed the causes of pica among pregnant women and reached similar conclusions to the animal studies with rats: that it was for the purposes of stress mediation. He concluded that women who engaged in pica during the second trimester of pregnancy "may have been under higher levels of stress early in pregnancy, but that this situation was placated by pica habit." The role of psycho-social stress in predisposing individuals to geophagia is also discussed in Singhi et al. (1981).

General pica and geophagia were reviewed by Parry-Jones and Parry-Jones (1992) and Reid (1992), respectively, with some similarity in etiologies proposed. For example, Reid, who discussed cultural and medical aspects of geophagia, provides documentation that the anemia is associated with, but not the cause of, geophagia. In some cultures, those groups who are at higher risk for anemia, e.g., pregnant women, are culturally sanctioned and encouraged to eat clay. In addition, there is significant evidence that clay, because of its cation exchange capacity, may provide an natural anti-diarrheal action and detoxify the body from toxins when they are consumed. The consumption of clay during famine would not only provide filler material for the stomach, but would tend to offset the gastric distress from consuming marginally acceptable plant material. The degree to which geophagia contributes to ameliorating mineral deficiencies in individuals is still unknown, but there is considerable evidence that clay consumption aggravates anemic conditions by preventing the absorption of iron and possibly zinc.

Parry-Jones and Parry-Jones (1992) discussed a wide variety of historical interpretations of pica and they conclude that, in the developed world, pica is now more rare and occurs mostly among infants and young children, particularly in low income socioeconomic groups. However, they also note that the habit or phenomenon, which is culture-bound in Third World countries, still persists. Those groups at higher risk can be either children or adults of either sex but mainly are those in poor, rural areas as well as pregnant women and those who are mentally handicapped.

Undifferentiated intakes

Some of the literature describing soil ingestion in specific cultures or ethnic groups has not differentiated between inadvertent and intentional intake. For example, in a number of tribal societies, e.g., the aboriginal population (Estlin and Gorton 1994), extreme values of soil intake have been reported. Some of these cases must be assumed as intentional ingestion. However, the environment in this case is dry and dusty and living conditions are primitive. Therefore, the conditions promote the likelihood of inadvertent ingestion. It seems likely that those societies that must necessarily accept living conditions which promote inadvertent ingestion may be predisposed to developing customs of intentional ingestion.

Literature that does not differentiate the nature of the intake is difficult to translate into data useful for modeling. The correct interpretation of the literature for the purpose of deriving estimates of soil ingestion-rate and other related parameters is particularly important in those instances where the magnitude of the possible exposure by soil ingestion rivals other pathways. Because inadvertent and intentional intake are separate phenomena they will usually have significantly different intake rates. Ideally, these phenomena should be separately evaluated in risk assessments. Many of the publications reviewed, however, did not make a distinction as to the cause or nature of the intake. In using such data, the uncertainty of generalizing to other members of the population should not go unaccounted.

DISCUSSION

Inadvertent soil ingestion will likely affect a larger proportion of any nationality or cultural or ethnic group than does geophagia. Because unintentional intake is generally many times smaller in magnitude than that typical of geophagia, the medical literature has focused very little attention on it. Inadvertent soil ingestion is more important to dose and risk assessment where collective dose is estimated because it will affect the collective radiation dose to a greater degree than a few isolated cases of geophagia. Whether inadvertent soil ingestion is important to any assessment question will depend greatly on the particular assessment objectives, environmental settings, cultural or ethnic groups, radionuclides involved and their individual chemical nature, and the possible dominance of other exposure pathways.

Definition of critical groups

The concept of the critical group was defined in ICRP Publication 26 (ICRP 1977, paragraph 85) as follows: "the group should be representative of those individuals in the population expected to receive the highest dose equivalent; the group should be small enough to be relatively homogeneous with respect to age, diet and those aspects of behavior that affect the doses received. . . ". ICRP goes on to recommend that although some members of the critical group may receive higher doses than the average member of the critical group, "it is important to select appropriate mean values for factors such as food consumption rates or occupancy parameters. . . " (ICRP 1985).

Consideration of soil ingestion will rarely determine a critical group except in the case of populations living on or using lands contaminated by actinides or transuranic elements. Because plant root uptake of actinides is low, generally $<10^{-4}$ for plutonium (Whicker and Schultz 1982), inhalation and direct soil ingestion will generally be the main routes of intake for those radionuclides. When the exposure pathways of the critical group does involve soil ingestion, the factors that will be important to defining that group will include the average inadvertent soil intake rate, the probability for geophagia to occur among members of the group, the solubility of the radionuclide(s) within the human body for the age or ethnic group being considered, and the dose coefficient (Sv Bq^{-1}) for that group. In the case of actinide contaminated lands, the critical group is likely to be children because of potentially higher ingestion rates and higher dose factors for the youngest ages.

For some combinations of radionuclides and culturally based habits, the subgroup most at risk for exposure via soil ingestion could be pregnant women or the developing fetus. Numerous publications have noted the incidence of geophagia among pregnant women (Ferguson and Keaton 1950; Edwards et al. 1959; Payton et al. 1960; Edwards et al. 1994). Horner et al. (1991) specifically noted that pica has been determined to be "not uncommon among pregnant women, particularly among rural black women [in the U.S.]". For many radionuclides, there are little data to model doses and consequential risk to the fetus; however, Harrison et al. (1991) discussed fetal doses for ^{239}Pu and ^{210}Po, and, more recently, Sikov et al. (1996) presented a comprehensive modeling approach.

The phases of life when geophagia is most likely practiced, i.e., childhood and periods of growth, pregnancy and lactation (Lanzkowsky 1959; Vessal et al. 1975), are the same periods when radiation exposure may have the most serious consequences. These reasons appear sufficient to warrant considering geophagia in risk assessments to these high-risk groups.

Geophagia and indigenous people

Predicting those cultural or ethnic groups of people who are at highest risk of geophagia is difficult because such predictions are dependent on the accuracy of literature and the representativeness of the observations that have been reported. In particular, the temporal accuracy of literature about cultures in Third World nations is limited by the high rate of economic, political, and cultural changes underway in many of these nations (Bodley 1982).

It seems clear from the literature, however, that those instances where geophagia is a cultural norm are generally among indigenous peoples. Indigenous peoples (also called "native" or "tribal" peoples) are found on every continent and constitute somewhere between 3.5% and 11% of the world's population (Durning 1993). Releases of radioactivity in different parts of the world may have different regional health impacts due to the varying number of people who have primitive or moderately primitive lifestyles. For example, in Africa and the Middle East there are between 25 and 350 million indigenous people (depending on the precise definition of indigenous), 80 million in East Asia, 3 million in Oceania (Australia and New Zealand), 80 million in South Asia, and 30–50 million in Southeast Asia. In the Americas there are 40 million indigenous people, including 2 million Native Americans in North America. While indigenous peoples constitute only about 1% of the U.S. population, in the rest of the Americas the percentage is considerably higher, ranging from 12% in Mexico to 70% in Bolivia.

The characteristics of indigenous peoples that result in a predisposition towards inadvertent ingestion and geophagia are (1) their close ties to the land as a means of sustenance, and (2) their almost universally poor economic conditions. Most all indigenous peoples live in, or maintain, a subsistence economy; many are, or are descendants of, hunters-gatherers, nomadic or seasonal herders, or peasant cultivators. Agriculture for most of these peoples is by manual labor, a practice which brings substantially greater contact with the soil than does mechanized agriculture.

Moreover, many of the countries having large numbers of indigenous peoples are also restricted to using over-grazed and over-utilized land, thus increasing even more the effort required to produce food and thus

enhancing their exposure to soil. The advance of the desert in overcrowded countries, caused by a cycle of excessive forest clearance, overgrazing and erosion, is often coupled with water scarcity and contributes to the likelihood of inadvertent soil intake. Africa, home to most of the world's indigenous peoples, has the largest number of the water scarce countries. Three-quarters of a billion people inhabit arid and semi-arid lands, about one-third of the world's land (Walton 1993), and twenty-six countries, home to more than 230 million people, are in the water-scarce category (Durning 1993).

Various lifestyle attributes of dry environments enhance inadvertent intake. For example, Giles et al. (1988) noted ten attributes of the aboriginal population that enhance the likelihood of soil intake: traveling on dusty roads in the back of open vehicles, living and sleeping in temporary structures with earth floors, recreational activities—particularly by children, living and eating in extremely dusty conditions, lack of adequate washing facilities, sitting on the ground and placing utensils on the ground, eating local biota, cooking food in earth ovens, storing uneaten food in the open where it is exposed to dust, and eating the partially stripped entrails of captured animals.

Anell and Lagercrantz (1958) summarized geophagous customs from around the world with extensive citations of reports and notes of field researchers of indigenous peoples. They summarized their findings on geophagia separately for Indonesia and Oceania, Africa and America.

Indonesia and Oceania. Anell and Lagercrantz (1958) found that geophagia was widespread and could be classified into four different categories: (1) earth-eating for medical reasons, (2) eating clay as regarded as a delicacy, spice, or source of enjoyment, (3) consuming clay or earth as a substitute for food, and (4) eating earth in conjunction with swearing of oaths. The impetus for geophagia in traditional medicine is mainly to assist pregnant women and as a remedy for diarrhea, dysentery, and other intestinal complaints. The innumerable reports that cite the ingestion of clays to relieve gastric disturbance and eliminate body toxins seems to be a well applied "folk medicine" that is continued today in commercial western culture. The clay kaolin is used in the commercial diarrhea medication Kaopectate.[†] Vermeer and Farrell (1985) reported that the clays consumed in Nigeria were of similar composition to the pharmaceutical. Geophagia is also practiced among pregnant woman for a number of reasons including to counter the frequent vomiting in early pregnancy, to cause the fetus to "rise" in the womb, which facilitates the delivery, to assist digestion, and to enhance the likelihood that the child will be born with a fairer complexion (a belief), or stronger and healthier. The phenomena is also consistent with worldwide reports of a longing for unusual foods and, in some cases, non-food items.

[†] Product of the Upjohn Company, Kalamazoo, Michigan 49001.

Africa. Anell and Lagercrantz (1958) reported geophagia to be a widespread phenomenon; in some regions, 80% of children ate earth up to the age of 5 y with 25% of the children consuming earth between the ages of 5 and 10 y. In some parts of the African continent, earth has been reported to be sold in loaves for consumption and is sometimes mixed with sugar and/or salt. The tendency to geophagia was reported to be more pronounced when crops fail or during other circumstances of scarcity (e.g., war, etc.). In general, geophagia is used as a means to appease hunger. Consuming earth is apparently used extensively as a remedy for syphilis as well as for diarrhea. The differences in geophagous practice between the sexes varies by geographic region. In some areas, girls encourage each other to consume earth at the onset of puberty; in other areas, it is more restricted to times of pregnancy. It is apparently a popular tradition that consuming earth facilitates the delivery of the child and is often thought to be necessary for the well-being of the fetus, and in Africa it is believed to ensure a dark complexion. Finally, the swearing of oaths frequently involves geophagia. In these instances, a person accused of a crime may be required to eat earth; the belief is that the perjurer will fall ill and die or become mentally deranged as punishment from the earth-divinity.

In general, the lifestyle and conditions under which indigenous peoples live result in a mandatory acceptance of the conditions that promote inadvertent soil intake. The strong association between primitive and often arid living conditions that encourage inadvertent ingestion and the frequent occurrence of geophagia suggest that the necessity of accepting poor conditions predisposes people to develop geophagous customs.

Only a few radiological risk assessments have been carried out specifically for indigenous peoples although numerous weapons production facilities as well as nuclear weapons tests sites used by various countries have been placed on lands traditionally used by native people. Specific groups of native people for which radiation risk assessment has been conducted include Native Americans on the Hanford reservation (see Heeb and Bates 1994), native Marshallese in the Marshall Islands (Simon and Graham 1996; Robison et al. 1997; Sun and Meinhold 1997), Australian aborigines at Maralinga (see Haywood and Smith 1990; Haywood and Smith 1992), native Kazaks living near Semipalatinsk, Kazakstan (see Rozenson et al. 1996), and natives of Brazil living near the site of the radiation accident in Goiania (Maletskos and Lipsztein 1991).

Review of selected literature of geophagia incidence and soil ingestion-rates

There are many dozens if not hundreds of publications that document qualitative and semi-quantitative observations of soil intake. Several previous reviews of historical literature have been published (e.g., Laufer 1930; Cooper 1957; Halsted 1968). Most of the studies cited refer to intentional intake, i.e., geophagia. The

selection of studies cited here (Tables 1 and 2) show the diversity of ethnic groups and conditions over which intentional soil ingestion has been observed. Several themes are recurring, e.g., ingestion during adolescence or pregnancy and to stave off chronic hunger. The studies cited in Table 1 are non-quantitative observations of geophagia while Table 2 presents studies that reported the frequency of geophagia. The studies of Table 2 have taken place for the most part during the last four decades; their value is for providing data on the prevalence of geophagia among those cultural and ethnic groups specifically observed.

There is a paucity of studies which have been specifically designed to determine soil ingestion rates; yet, a number of publications have reported quantitative values of intake rates (see Table 3). Only four rigorously conducted empirical studies to quantify soil ingestion are noted in the English literature: Binder et al. (1986); Calabrese et al. (1989); van Wijnen et al. (1990) and Davis et al. (1990). These studies focus on inadvertent intake. Their findings provide ingestion rate estimates that are likely suitable for typical U.S. or European populations. These four studies do not address, however, the special situations of high risk occupations, primitive living conditions, or indigenous peoples living in a subsistence economy; furthermore, these studies address only to a limited degree the child or adult who intentionally eats soil.

The empirically based studies are not without their own problems. In particular, widely varying intake rate estimates for the same group have been observed depending on the trace element measured. For example, Binder et al. (1986), in a study of 59 children 1–3 y of age in East Helena, Montana, determined estimates of 181 and 184 mg d^{-1} using Al and Si tracers, respectively, and 1834 mg d^{-1} using Ti (based on fecal analysis). The other three empirical studies also exhibited the same problem to some degree. Calabrese and Stanek (1994) have discussed the source of these variations and attributed it to conditions where the tracer element is excessively high in the ingested foods as compared to the soil that is under consideration. Errors in specifying the fecal sampling period relative to the period of ingestion was also implicated in causing calculation errors.

Most of the reported values in Table 3, other than the previous four studies discussed, have little empirical basis. The few that do (e.g., Linsalata and Eisenbud 1986 or Wong et al. 1988) may not be easily generalized except where conditions are similar as where the study was conducted. The reported intake rate estimates for the citations in Table 3 generally apply to single individuals or to a small group that was observed for a short period of time. Publications in this table are cited without requirements as to the precision or origin of the data.

Those publications providing quantitative values of soil intake rates (Table 3) can be loosely divided into those based on (1) direct measurements of soil tracer elements in feces (Binder et al. 1986; Linsalata and Eisenbud 1986; Clausing et al. 1987; Wong et al. 1988; Calabrese et al. 1989; Davis et al. 1990; van Wijnen et al. 1990); (2) indirect measurements[‡] (Lepow et al. 1974; Day et al. 1975; Fisher et al. 1981; de Silva 1994); (3) estimation—based on a variety of kinds of evidence (Gelfand et al. 1975; Wedeen et al. 1978; Vermeer and Frate 1979; NRC 1980; Kimbrough et al. 1984; Haywood and Smith 1990; Haywood and Smith 1992), (4) assumption or speculation (Martin and Bloom 1975; Rogers 1975; Healy 1977; Finley et al. 1994), and (5) literature review (Finley et al. 1994; Sheppard 1995). Some papers have used more than one of these methods to arrive at intake values.

Most of the publications cited in Table 3 refer to populations in the U.S.; the exceptions reported findings in Brazil (Linsalata and Eisenbud 1986), Jamaica (Wong 1988), Australia (Haywood and Smith 1990; Haywood and Smith 1992), and the Netherlands (van Wijnen et al. 1990). A few of the papers include non-white populations, e.g., black (Gelfand et al. 1975; Wedeen et al. 1978; Vermeer and Frate 1979), Native American (Fisher et al. 1981), Jamaican (Wong 1988), and aboriginal (Haywood and Smith 1990; Haywood and Smith 1992).

Those studies noted in Table 3 that focus on intake by children are probably the most reliable; there is considerable agreement on this point in the literature. Intakes of soil by adults is much more controversial among reporting authors. Soil ingestion among adults is believed by this author to be mainly a function of occupation in western societies or a function of environment, cultural norms, and life-style attributes for indigenous peoples.

Although the intake rate estimates of Haywood and Smith (1990, 1992) are experimentally unconfirmed, their estimated values (up to 10 g d^{-1}) for the aboriginal population of the Maralinga district in Australia point out that extreme values of inadvertent intake might occur under primitive lifestyles and within dry environments. However, not all rural living conditions will result in extraordinarily high intakes. Linsalata and Eisenbud (1986), for example, found relatively modest intakes of 200 mg d^{-1} for a farming community in Brazil. Presumably, the degree of vegetative ground cover—a function of the regional climate, as well as life-style—are important factors that influence intake rates.

Cultural norms with respect to geophagia, even across the U.S., may vary significantly. Vermeer and Frate (1979) investigated geophagia in rural Mississippi in 50 households containing 229 individuals. In this study, the individual had to admit to consumption of clay to be considered a practitioner of geophagia. Therefore, the data were believed to represent a minimum of the true incidence. The nutrition survey administered did not uncover any geophagia among adult males or adolescents of either sex but identified 57% of the women and 16% of the children (ages 1–4 y) as geophagic. In particular,

[‡] An example of indirect measurement would be measuring the amount of dirt that could adhere to a lollipop and the number of times the candy is observed to be taken in and out of the child's mouth during eating.

50% of the pregnant women practiced geophagia. Average daily consumption of clay was reported to be 50 g; the values were determined as a portion or multiple of the amount held in a cupped hand.

Despite beliefs of some authors that geophagia in rural areas or among children with normal mental faculties is diminishing, within the last 10 y geophagia has been noted not to be a rare event. In reports by Wong (1988) and Wong et al. (1988), children institutionalized in two homes in Jamaica were studied for geophagous behavior over a period of 4 mo to assess the risk of exposure to geohelminth infection. Wong determined from analysis of fecal levels of dietary silica that 33% and 66% of children from the two homes practiced geophagia and that some children ingested up to 10 g soil d^{-1}. However, 20% of the children accounted for greater than 60% of the soil ingested. Several mentally disturbed children consumed on occasion up to 60 g soil d^{-1}. In the study by Wong, 21% of the children with normal mental capabilities with an average age of 3.1 y displayed geophagia occasionally with ingestion rates >1 g d^{-1}, and in 10.5% of all observations of 24 children, ingestion was greater than 1 g d^{-1}. Calabrese and Stanek (1993) reviewed the dissertation by Wong (1988) and concluded that the high prevalence of geophagia among these normal children challenges previous assumptions that geophagia is a rare condition.

The data presented in Table 3 are difficult to generalize. Estimates of intake rates vary considerably for different ethnic groups and among different studies. There appears to be a general consensus that among adults in western society who do not routinely contact the soil by occupation or hobby, intake of soil is very low—probably on the order of a few milligrams to a few tens of milligrams per day. However, soil intake by children and pregnant women, even in western societies, is poorly understood. Determining relevant intake rates for specially defined critical interest groups and/or populations considered non-traditional by western standards will require the greatest care. Intake rate estimates can only be reliably made with extensive knowledge of the living conditions and cultural attitudes of the population of interest.

Variability and uncertainty

A central issue to using literature data to make dose and risk assessments is to determine the relevant variation of soil ingestion among members of the population under consideration or to estimate the uncertainty associated with assumed mean intake rates for identified or representative members of the group. Many chemical risk assessments have used the EPA default values (EPA 1989a, b, c; EPA 1990a) or other point estimates of soil ingestion rates for risk calculations, culminating in point estimates of risk. In recent years, radiological assessment modeling has led most types of risk assessments in mathematical sophistication, typically using stochastic or Monte-Carlo calculations. Stochastic calculations require a specified distribution for each model parameter, though variability and uncertainty are often confused and improperly combined (Hattis and Burmaster 1994; Hoffman and Hammonds 1994).

Properly conducted probabilistic assessment modeling constitutes the state-of-the-art and requires distributions of alternative values for parameters. These distributions are used to determine either a range of exposures (Hattis and Burmaster 1994) among a population or the uncertainty for an identified or representative individual. The few distributions available in the literature thus far fall severely short of taking into account the various sex, age, seasonal, cultural, occupational and ethnic-specific variations and combinations. Despite the rather adequate body of literature that documents the occurrence of soil ingestion, at present there is not sufficient information to adequately assess true variability within any single group or uncertainty of mean intake values.

A few publications have attempted to model the variability distribution of intake rates among a population. For example, Thompson and Burmaster (1991) reported parametric distributions of soil ingestion by children as interpreted from the data of Binder et al. (1986). Finley et al. (1994) discussed the need to develop standard probability distributions to model intake and other exposure parameters and fitted the soil intake data for children reported by Stanek and Calabrese (1992) to a population distribution. For children they give the 5th, 10th, 25th, 50th, 75th, 90th and 95th percentiles as 0, 0, 0, 16, 45, 67 and 110 mg d^{-1}, respectively. For adults, they state that there are no reliable soil ingestion data. This reference does not provide any reference distributions for non-western populations or high risk groups, e.g., pregnant women.

A number of specific studies, however, have noted conditions that affect the variability of soil ingestion. For example, Barltrop (1979) commented on the importance of the seasonal dependence of lead in blood levels of children, linking the higher intake with weather conditions which encouraged outdoor activities. In that study, blood levels of lead were greater in the summer than in the spring. In addition, children had consistently greater blood concentrations than mothers. Although there were many potentially confounding variables, the need for recognition of age and seasonal dependence was emphasized. In addition, Baltrop noted that dietary practices and nutritional status may determine the magnitude of the lead absorbed (via soil ingestion). Thus variability of measurement data among a group may be dependent on many factors including the individual's ability to absorb soil contaminants through the gastrointestinal system.

Use of soil ingestion data in radiation dose calculations

The endpoint of radiation dose assessments is a determination of whole-body or organ dose for identified individuals, a representative individual, a population in a defined geographic area, or to a critical population subgroup that is composed of individuals whose occupations, recreational activities, or lifestyles would likely lead to the highest exposure.

The modeling of soil intake has several variations depending on the number of factors that are used to specify the intake and its temporal variation. One method discussed in the literature pertains mainly to the ingestion of chemicals in soil and is presented here only for review purposes. For example, EPA (1989c, Exhibit 6–14) and ATSDR (1992, Exhibit D.3) give the following formulation to estimate intake (mg of chemical) normalized to body weight (kg):

$$\text{Intake (mg kg}^{-1}\text{d}^{-1}) = (CS \times IR \times CF \times FI \times EF \times ED)/(BW \times AT), \quad (1)$$

where

CS = chemical concentration in soil (mg kg^{-1}, site specific);
IR = ingestion rate (mg soil d^{-1}, see below);
CF = conversion factor (10^{-6} kg mg^{-1});
FI = fraction ingestion from contaminated source (unitless, pathway specific);
EF = exposure frequency (365 d y^{-1});
ED = exposure duration (y, 70 lifetime, 90th percentile at one residence is 30 y, 50th percentile at one residence is 9 y);
BW = body weight (kg, 70 for adult, 16 for children 1–6 y); and
AT = averaging time, i.e., period over which exposure is averaged (d, $ED \times 365$ d y^{-1} for noncarcinogenic effects, 70 y $\times$ 365 d y^{-1} for carcinogenic effects).

For exposures to chemicals, EPA recommends ingestion-rates (IR) of 200 mg d^{-1} for children 1–6 y and 100 mg d^{-1} for ages greater than 6 y (EPA 1989b). EPA notes that these values could change based on site-specific data or new research findings and that they do not pertain to incidences of geophagia. The recommended values for the other parameters are shown in parentheses above. ATSDR (1992) cites similar but somewhat smaller values based on Davis et al. (1990), Calabrese et al. (1989), and Calabrese et al. (1990): 50–100 mg d^{-1} for non-pica children, 50 mg d^{-1} for adults. They also note that for pica behavior, soil ingestion rates may be 5 to 10 g d^{-1}.

EPA (1989c, P.10–24) notes the differences in chemical and radioactivity dose calculations. They suggest eliminating averaging time and body weight from the denominator, particularly when age-dependence is included in the radiation dose factor.

A more straight-forward calculation of radiation dose to an individual from ingested radioactivity in soil would use the product of the average daily intake rate of soil (g d^{-1}) and the average concentration of radioactivity in soil (Bq g^{-1}):

$$D_{soil} = C_{soil} \times I_{soil} \times ED \times DF, \quad (2)$$

where,

D_{soil} = effective committed dose from ingestion of radioactively contaminated soil (Sv);
C_{soil} = average concentration in soil of a single radionuclide (Bq g^{-1});
I_{soil} = average daily ingestion rate of soil during the exposure period (g d^{-1});
ED = exposure duration (d); and
DF = dose factor (Sv Bq^{-1}).

If the time period of ingestion were a single year, then ED could be set equal to ($f_i \times 365$ d), where f_i is the fraction of the year when soil ingestion might take place (e.g., during spring and summer months, etc.). For the case of geophagia, the dose to a person assumed to practice the habit can be calculated by substituting a more relevant intake rate.

In collective dose calculations, only a small proportion of the population can be assumed to be at risk of practicing geophagia, thus, the dose must be computed separately for those only having inadvertent intakes and those practicing geophagia:

$$D_{collective\ soil} = \Sigma_a\{[C_{soil} \times II(a)_{soil} \times ED \times DF(a) \times N(a) \times PI(a)]_{inad} + [C_{soil} \times IG(a)_{soil} \times ED \times DF(a) \times N(a) \times PG(a)]_{geo}\}, \quad (3)$$

where

$D_{collective\ soil}$ = collective dose from radioactivity as a result of soil ingestion (person-Sv);
a = age at exposure (y);
$II(a)_{soil}$ = average daily inadvertent ingestion rate of soil (age-dependent) during the exposure period (g d^{-1});
$DF(a)$ = age dependent dose coefficient (Sv Bq^{-1});
$N(a)$ = number of persons potentially exposed to soil radioactivity (age-dependent);
$PI(a)$ = proportion of persons (age-dependent) assumed to have inadvertent intakes;
$IG(a)_{soil}$ = average daily ingestion rate of soil for geophagia (age-dependent) during the exposure period (g d^{-1}); and
$PG(a)$ = proportion of persons (age-dependent) assumed to practice geophagia.

Further refinements are possible for dose calculations for representative individuals by modifying default ingestion rates for seasonal and occupational specificity. The previous equations could incorporate such modifying factors, although numerous assumptions are required to parameterize data for those modifiers. For example,

$$D_{soil} = C_{soil} \times I_{soil} \times ED \times EF \times DF \times RF \times OF \times RUF \times SF, \quad (4)$$

where

EF = exposure frequency (d y^{-1});
OF = occupational exposure modification factor;
RUF = rural/urban modification factor; and
SF = seasonal modification factor (could account for differences in availability of soil or other phenomenon not accounted for in more specific factors).

In Table 4, different exposure categories are defined with unique II and IG values. An RUF is not used because rural and urban scenarios are individually defined. Values for the SF factor are not presented; values would necessarily have to be site-specific. An alternative to SF factors is to specify all model parameter values for different climatic regimes (e.g., temperate, tropical, etc.; see Table 4 for examples).

Recommendations of soil ingestion parameters based on available literature

Some recommendations have been offered in the literature and by U.S. regulatory agencies for default soil ingestion rates (for example, ATSDR 1992, Exhibit D.3; Kimbrough et al. 1984; EPA 1989a, b, c, Exhibit 6–14; EPA 1990a; Calabrese et al. 1992; Calabrese and Stanek 1994; Sheppard 1995). For example, ATSDR (1992) provides soil ingestion values for CERCLA and RCRA mandated assessments. The ATSDR Public Health Assessment Guidance Manual (1992) gives values of 50 to 100 mg d^{-1} for non-pica children, 50 mg d^{-1} for adults and states that 5–10 g d^{-1} are possible intakes of children with pica behavior. Their primary sources of data were Calabrese et al. (1989), Davis et al. (1990) and Calabrese et al. (1990).

In a series of risk assessment guidance publications (EPA 1989a, b, c), EPA recommends the use of similar values for soil ingestion: 200 mg d^{-1} for children and 100 mg d^{-1} for adults.

Calabrese et al. (1992) and Calabrese and Stanek (1994) made the following recommendations, which were intended to be conservative, upper-bound estimates: (1) Assume that 2% of children aged 1–6 y exhibit soil pica of 1 g d^{-1}; (2) Assume that 0.2% of children ingest 10 g d^{-1} from ages 1 through 6 y. They also provided estimates intended to be more realistic; (1) Assume 1% of children exhibit soil pica of 1 g d^{-1} for 4 d wk^{-1} and 500 mg d^{-1} for 3 d wk^{-1} for 4 y; (2) Assume that 0.2% of children ingest 10 g d^{-1} for 3 d wk^{-1} and 200 mg d^{-1} for 4 d wk^{-1} for 4 y.

Revisions of the Calabrese ingestion rates emphasized the need to have wide uncertainty distributions that allow for high values to occur with finite probability (Stanek and Calabrese 1995). Consequently, a lognormal distribution was assigned here to represent the range of possible alternative values with a geometric standard deviation (GSD) of 3.2 for adults and 4.2 for children. This degree of uncertainty results in an upper 95th percentile for children equal to 100 mg $d^{-1} \times (4.2)^2$ or 1.764 mg d^{-1}, a value in agreement with the revised data of Stanek and Calabrese.

A compilation of possible distributions of intake rates and other soil-ingestion parameters based on this author's judgment after reviewing the literature cited in this report is provided in Table 4. The central estimates are consistent with the consensus of numerous authors that 100 mg d^{-1} represents a reasonable value of intake for children. However, in light of the sparse data for many scenarios, the distributions in Table 4 are intended to present a wide range of possible alternative values around a central value. The ranges may be assumed to represent a subjective 95% ($\pm 2\sigma$) confidence interval for a representative individual. The distribution types could arguably be changed, e.g., to a rectangular distribution (equal probability over the entire range). The shape of the distribution as well as central estimate should be determined for specific uses based on the subjective confidence of the applicability of the data for the particular exposure situation.

A possible use of the distributions provided in Table 4 would be for use in assessments that fit the scenario described. The distributions serve as examples of the type of information that is needed for a variety of risk assessment purposes. It should be understood that the values and ranges presented in Table 4 represent a subjective determination of the central tendency, and an appropriate spread was determined from examining numerous literature citations, rather than by conducting a statistical analysis of available data.

Other authors have examined various population groups and refused to offer recommendations of ingestion rates because of the lack of evidence. For example, Finley et al. (1994) stated that it was inappropriate at the time of their publication to recommend a standard distribution for typical adults in the U.S. because of the paucity of data available. It should be recognized though that subjective uncertainty distributions (as provided in Table 4) are developed precisely for the case where lack of knowledge predominates.

It should be emphasized that the values in Table 4 may not have relevance to a specific group of interest. Caution is suggested in using these values as with any literature values. The lengthy citation list is offered to assist risk-assessment modelers in determining relevant values for specific scenarios.

Evaluation of current environmental radiation dose assessment models for soil ingestion

A variety of recent radiation dose- or risk-assessment models and recently conducted assessments were reviewed to determine if soil ingestion, either inadvertent or intentional, was included (see Table 5). Some models reviewed, e.g., DOSDIM and SCK-CEN BIOSPHERE did not include soil ingestion for reasons that within the country of origin and its normal climate (e.g., the wet climate of Belgium), soil ingestion is believed not to substantially contribute to the total dose.[§] Other models did not include direct soil ingestion by

[§] Personal communication, N. Lewcyckyj, SCK-CEN, B-2400 MOL, Belgium; March 1995.

Table 4. Suggested values of soil ingestion model parameters for various lifestyle scenarios. NOTE: These parameter values are presented either as triangular distributions, specified as Tri(minimum, mode, maximum) or lognormal distributions, specified as LN(geometric mean, geometric standard deviation). The distributions should be considered to be a set of alternative parameter values that might be relevant to representative members of a population and that the distributions account for lack of knowledge uncertainty. The reader is cautioned that neither the central estimates or any specific quantile value from the distributions have been rigorously validated for any specific population. "Child" refers approximately to ages 1 through 6 y. Categories 1–7 may apply to localized populations within the United States or elsewhere depending on the knowledge or judgement of the risk assessor. Categories 8 and 9 would have greater applicability for scenarios outside of the U.S. The parameter definitions refer to eqns (2), (3) and (4).

Parameter definitions:

I = II or IG, ingestion rate (g d^{-1});
ED = exposure duration (y)[a];
EF = exposure frequency (d y^{-1}): temperature climate or tropical climate;
DF = dose coefficient (Sv Bq^{-1} ingested);
OF = occupational factor (unitless), accounts for high/medium/low risk practices, e.g., occupations, type of activities (plowing, earthmoving, etc.), hobbies or communal responsibilities for indigenous peoples; values can be altered if specific occupational information is known or assumed;
P = proportion of population likely to engage in geophagia;
U_i = multiplicative uncertainty factor, to be determined[b] (dependent on data or judgement).

	Inadvertent ingestion	Geophagia	Inadvertent ingestion	Geophagia
(1) Occupations on tilled agricultural land (no homes)—bare part of year, vegetated part of year.				
I =	LN(0.1, 3.2)	0	0	0
ED =	1	—	—	
EF (temperate climate) =	Tri(180, 270, 360)	—		
EF (tropical climate) =	Tri(240, 300, 360)	—		
DF =	Tri(DF/U_f, DF, DF × U_f)	—		
OF =	Tri(0.5, 1.0, 2.0)			
P =	—			
(2) Occupations on pasture land (no homes)—heavily vegetated.				
I =	LN(0.05, 3.2)	0	0	0
ED =	1	—	—	
EF (temperate climate) =	Tri(180, 270, 360)			
EF (tropical climate) =	Tri(240, 300, 360)			
DF =	Tri(DF/U_f, DF, DF × U_f)			—
OF =	Tri(0.5, 1.0, 2.0)	—		—
P =	—	—		
(3) Occupations on pasture land (no homes)—sparsely vegetated, range land for grazing.				
I =	LN(0.1, 3.2)		0	0
ED =	1			—
EF (temperate climate) =	Tri(180, 270, 360)		—	
EF (tropical climate) =	Tri(240, 300, 360)		—	
DF =	Tri(DF/U_f, DF, DF × U_f)			
OF =	Tri(0.5, 1.0, 2.0)			
P =	—			
(4) Occupations at construction sites (no homes)—disturbed by earth-moving, traffic, bulldozing, etc				
I =	LN(0.1, 3.2)	0	0	0
ED =	1	—	—	
EF (temperate climate) =	Tri(90, 180, 270)	—	—	
EF (tropical climate) =	Tri(150, 270, 360)	—		
DF =	Tri(DF/U_f, DF, DF × U_f)	—	—	
OF =	Tri(0.5, 1.0, 2.0)	—	—	
P =	—	—		

(5) Rural lifestyles (w/homes)—heavily vegetated, forests and fields.				
I =	LN(0.1, 3.2)	Tri(1.0, 3.0, 5.0)	LN(0.1, 4.2)	Tri(1.0, 3.0, 5.0)
ED =	1	1	1	1
EF (temperate climate) =	Tri(180, 270, 360)	Tri(180, 270, 360)	Tri(180, 270, 360)	Tri(180, 270, 360)
EF (tropical climate) =	Tri(240, 300, 360)	Tri(240, 300, 360)	Tri(240, 300, 360)	Tri(240, 300, 360)
DF =	Tri(DF/U_f, DF, DF × U_f)	Tri(DF/U_f, DF, DF × U_f)	Tri(DF/U_f, DF, DF × U_f)	Tri(DF/U_f, DF, DF × U_f)
OF =	Tri(0.5, 1.0, 2.0)	Tri(0.5, 1.0, 2.0)	1	1
P =	—	Tri(0.005, 0.01, 0.02)	—	Tri(0.05, 0.10, 0.30)
(6) Rural lifestyles (w/homes)—sparsely vegetated.				
I =	LN(0.2, 3.2)	Tri(1.0, 3.0, 5.0)	LN(0.2, 4.2)	Tri(1.0, 3.0, 5.0)
ED =	1	1	1	1
EF (temperate climate) =	Tri(180, 270, 360)	Tri(180, 270, 360)	Tri(180, 270, 360)	Tri(180, 270, 360)
EF (tropical climate) =	Tri(240, 300, 360)	Tri(240, 300, 360)	Tri(240, 300, 360)	Tri(240, 300, 360)
DF =	Tri(DF/U_f, DF, DF × U_f)	Tri(DF/U_f, DF, DF × U_f)	Tri(DF/U_f, DF, DF × U_f)	Tri(DF/U_f, DF, DF × U_f)
OF =	Tri(0.5, 1.0, 2.0)	Tri(0.5, 1.0, 2.0)	1	1
P =	—	Tri(0.005, 0.01, 0.02)	—	Tri(0.05, 0.10, 0.30)
(7) Suburban lifestyles (w/homes)—including lawns, parks, recreational areas, some gardens.				
I =	LN(0.1, 3.2)	Tri(1.0, 3.0, 5.0)	LN(0.1, 4.2)	Tri(1.0, 3.0, 5.0)
ED =	1	1	1	1
EF (temperate climate) =	Tri(180, 270, 360)	Tri(180, 270, 360)	Tri(180, 270, 360)	Tri(180, 270, 360)
EF (tropical climate) =	Tri(240, 300, 360)	Tri(240, 300, 360)	Tri(240, 300, 360)	Tri(240, 300, 360)
DF =	Tri(DF/U_f, DF, DF × U_f)	Tri(DF/U_f, DF, DF × U_f)	Tri(DF/U_f, DF, DF × U_f)	Tri(DF/U_f, DF, DF × U_f)
OF =	Tri(0.5, 1.0, 2.0)	Tri(0.5, 1.0, 2.0)	1	1
P =	—	Tri(0.005, 0.01, 0.02)	—	Tri(0.05, 0.10, 0.30)
(8) Lifestyles of indigenous peoples (mainly hunters/food gathering/nomadic societies)—wet climates/regions of thick ground vegetation.				
I =	LN(1.0, 3.0)	Tri(1.0, 3.0, 10.0)	LN(3.0, 4.0)	Tri(2.0, 5.0, 10.0)
ED =	1	1	1	1
EF (temperate climate) =	Tri(180, 270, 360)	Tri(180, 270, 360)	Tri(180, 270, 360)	Tri(180, 270, 360)
EF (tropical climate) =	Tri(240, 300, 360)	Tri(240, 300, 360)	Tri(240, 300, 360)	Tri(240, 300, 360)
DF =	Tri(DF/U_f, DF, DF × U_f)	Tri(DF/U_f, DF, DF × U_f)	Tri(DF/U_f, DF, DF × U_f)	Tri(DF/U_f, DF, DF × U_f)
OF =	Tri(0.5, 1.0, 2.0)	Tri(0.5, 1.0, 2.0)	1	1
P =	—	Tri(0.01, 0.05, 0.10)	—	Tri(0.10, 0.30, 0.50)
(9) Lifestyles of indigenous peoples (mainly hunters/food gathering/nomadic societies)—dry climates/regions of sparse vegetation.				
I =	LN(2.0, 3.0)	Tri(1.0, 3.0, 10.0)	LN(3.0, 4.0)	Tri(2.0, 5.0, 10.0)
ED =	1	1	1	1
EF (temperate climate) =	Tri(180, 270, 360)	Tri(180, 270, 360)	Tri(180, 270, 360)	Tri(180, 270, 360)
EF (tropical climate) =	Tri(240, 300, 360)	Tri(240, 300, 360)	Tri(240, 300, 360)	Tri(240, 300, 360)
DF =	Tri(DF/U_f, DF, DF × U_f)	Tri(DF/U_f, DF, DF × U_f)	Tri(DF/U_f, DF, DF × U_f)	Tri(DF/U_f, DF, DF × U_f)
OF =	Tri(0.5, 1.0, 2.0)	Tri(0.5, 1.0, 2.0)	1	1
P =	—	Tri(0.01, 0.05, 0.10)	—	Tri(0.10, 0.30, 0.50)

[a] Set equal to 1.0 to compute annual dose.

[b] For example, if the uncertainty factor (U_f) was subjectively determined as 4.0; the minimum, mode, and maximum would then equal DF/4.0, DF, DF × 4.0, respectively.

Table 5. Review of recent radiation dose/risk assessment models in accounting for ingestion of soil by humans.

Model name (country of origin)	Literature source (year of citation)	Soil ingestion Y/N?	Type of ingestion: Inadvertent, intentional or not distinguished (ND)	Intake-rates[a]	Source of intake-rate data
GENII (U.S.)	Napier et al. (1988)	Y	ND	age averaged: 410 mg d^{-1} 0–9 mo: 0 mg d^{-1} 9–18 mo: 1000 mg d^{-1} 1.5–3 y: 10,000 mg d^{-1} 3.5–5 y: 1000 mg d^{-1} >5 y: 100 mg d^{-1}	Kimbrough et al. (1984)
PATHWAY (U.S.)	Whicker et al. (1990)	N, except for rainsplash on vegetables		—	Dreicer et al. (1984)
CALDOSE (Canada)	Zach and Sheppard (1991)	Y	Inad	10 mg d^{-1} (from hands) 5×10^{-4} dry soil kg^{-1} vegetables wet wt. from rainsplash total = 250 mg d^{-1}	Hawley (1985) LaGoy (1987) Dreicer et al. (1984)
MMSOILS (U.S.)[b]	EPA (1992)	Y	Inad	200 mg d^{-1} children 100 mg d^{-1} adult	Risk Assessment Guidance for Superfund (EPA 1989a,b,c)
ECOSYS-87 (Germany)	Muller and Pohl (1993)	N, except for rainsplash on vegetables		—	Dreicer et al. (1984)
RESRAD (U.S.)	Yu et al. (1993)[c]	Y	Inad	200 mg d^{-1} children 100 mg d^{-1} adult	Risk Assessment Guidance for Superfund (EPA 1989a,b,c)
COMIDA (U.S.)	Abbott and Rood (1994)	N, except for rainsplash on vegetables		—	Dreicer et al. (1984)
BIOTRAC (Canada)	Zach et al. (1994)	Y	Inad	100 mg d^{-1} (from hands) 5×10^{-4} dry soil kg^{-1} vegetables wet wt. from rainsplash	Hawley (1985) LaGoy (1987) Dreicer et al. (1984)
MEPAS (U.S.)	Buck et al. (1995)	Y	Inad	200 mg d^{-1} children 100 mg d^{-1} adult	Risk Assessment Guidance for Superfund (EPA 1989)
SCK · CEN BIOSPHERE (Belgium)	Zeevaert et al. (1995)	N	—	—	(noted not to be important in climate of concern)
PRESTO-WIN (U.S.)	(1995)[d]	Y	Inad	200 mg d^{-1} children 100 mg d^{-1} adult	Risk Assessment Guidance for Superfund (EPA 1989a,b,c)
DOSDIM (Belgium)	(1995)[e]	N	—	—	(noted not to be important in climate of concern)

[a] Intake-rates shown are model default values; some models have modifiable user inputs.
[b] MMSOILS does not determine risks from radionuclides—only chemical contaminants.
[c] Poster presentation for RESRAD-BASELINE at 40th annual Health Physics Meeting, Boston, MA, 23–27 July 1995.
[d] Personal communication, D. E. Fields, J. J. Melescue 1995, based on methodology described in Fields et al. (1986).
[e] Personal communication, N. Lewcyckyj, March 1995.

humans but did include soil rainsplash onto vegetables; those models included PATHWAY (Whicker et al. 1990), ECOSYS-87 (Muller and Prohl 1993), and COMIDA (Abbott and Rood 1994).

Several models did explicitly include soil ingestion by humans. Four models developed in the U.S. use the assumptions of the EPA (EPA 1989a, b, c; EPA 1990a) risk assessment guidance for Superfund. Those models include PRESTO-WIN (based on Fields et al. 1986), MMSOILS[‖] (EPA 1992), RESRAD (Yu et al. 1993), and MEPAS (Buck et al. 1995).

The BIOTRAC model (Zach et al. 1994) for assessing radiological doses from long term waste disposal explicitly includes inadvertent soil ingestion. The ingestion rate from soil adhering to hands is assumed to be 100 mg d^{-1}, based on Hawley (1985) and LaGoy (1987), and soil contamination on vegetables is assumed as 5×10^{-4} kg dry soil kg^{-1} wet biomass as a result of rainsplash (Dreicer et al. 1984). There is no age-dependence and uncertainty is accounted for by related parameters[¶] in BIOTRAC. CALDOSE (Zach and Sheppard 1991) assumes 250 mg d^{-1} total intake via ingestion, dirt from hands, and rainsplash onto vegetables.

The GENIE model (Napier et al. 1988) also explicitly accounts for soil ingestion; it uses intake rates derived from theoretical calculations reported by Kimbrough et al. (1984)[#] (see Table 3). Those rates, particularly for children between 1.5 and 3 y, are better representative of geophagic behavior or possibly primitive living conditions.

No models were explicit in accounting for intentional soil ingestion but many of the models had modifiable user inputs, thus allowing for calculations for non-typical scenarios.

Several recently published radiation dose assessments were also reviewed to determine if soil ingestion was explicitly accounted for. A report on an historical dose evaluation for the Idaho National Engineering Laboratory did not indicate any direct pathway from soil to humans (Chew et al. 1993; Otis and Case 1993). The Hanford Environmental Dose Reconstruction Project, summarized in numerous reports (see for example TSP 1994), did not include soil ingestion for ^{131}I (Napier 1992) because of its minimal contribution, but did account for it for other radionuclides (Farris 1994). In the latter report, ingestion rates of 1,000 mg d^{-1} for infants and 100 mg d^{-1} for adults were used. Distributions were assigned as uniform and ranged over one order of magnitude.

Several dose assessments have been conducted recently for residents of Rongelap Atoll in the Marshall Islands, a coral atoll that received heavy amounts of radioactive fallout from a thermonuclear weapon test in 1954. An assessment by Kohn (1989) indicated that ingestion of soil should be considered in the assessment of dose to children as a result of residual transuranic activity in the soil. Subsequently, assessments for Rongelap by SMT (1995), NRC (1994); Robison et al. (1994) and Sun and Meinhold (1997) have considered this issue. NRC and Robison et al. used intake rates in their calculations of 100 mg d^{-1} for all ages except for infants whereas Sun and Meinhold assumed an average lifetime intake of 500 mg d^{-1}.

The overall lack of consistency in the estimation of soil ingestion parameters in various radiological assessments and/or assessment models could be a result of different assessment needs, but it is evident that those models that have included direct soil ingestion cite little of the literature base from which they draw data. Moreover, all the models that did not include soil ingestion did not necessarily rule it out because it was determined to be insignificant. The various papers cited in Tables 3 and 4 are recommended for further review by assessment modelers for the purpose of determining the necessity of including soil ingestion into their particular model.

Unresolved issues

Though there is little dispute that soil ingestion is not uncommon, there are numerous unresolved issues concerning the modeling of soil ingestion in dose assessment calculations. This paper is written, in part, to stimulate thinking about the various issues noted below:

- Many documented instances of intentional soil ingestion describe the consumption of clay soils, which are apparently more palatable and better relieve gastric ailments than do coarser soils. Clay soils are often removed from excavation pits, locations which in many cases are below the depth at which surface deposits of radioactivity might penetrate. This generalization would not hold in all circumstances, however, and there remains a finite possibility that individuals who eat clay might encounter radioactively contaminated soil. Even in the absence of technologically enhanced contamination, routine but inadvertent intake of soil will result in some individuals ingesting small amounts of naturally occurring radioactivity. Clay could contribute, in particular, naturally occurring radioisotopes of the uranium and thorium chains.
- The question must be asked whether radioactivity ingested with clay would be unavailable for absorption in the human body because of the clay's binding capacity. Evidence appears to be contradictory as to the effectiveness of clay for binding elements in trace quantities within the acidic environment of the stomach and intestine. For example, anemia, particularly iron and zinc deficiency, is believed to be associated with clay ingestion. This tends to indicate that the binding capacity of clay might prevent bodily absorption

‖ MMSOILS does not asssess radiation risk, only risk from chemicals.

¶ Personal communication, R. Zach, AECL Research, Pinawa, Manitoba, Canada R0E 1L0; March 1995.

Personal communication, B. Napier, Battelle, Pacific Northwest National Laboratory, PO Box 999, Richland, WA 99352; February 1995.

of certain elements from the intestine. Reid (1992) notes the complexity of the phenomenon in that clays from different geographic locations differ in their effectiveness for blocking absorption of elemental iron. In other studies, both fluoride and potassium poisoning (Gelfand et al. 1975; Fisher et al. 1981) have been associated with excessive clay ingestion because of the high concentrations of these elements in certain types of clays. Thus, the importance of clay soils to the internal absorption of radioactivity is not yet resolved and may not be easily generalized due to differences in clay types.

- The contamination level of soil that would be likely ingested is a particularly difficult issue. Contamination levels of the near-surface soil horizons will vary among different sites, with the chemical nature of the radioactivity, with the composition and physical characteristics of the soil, with the local climatic conditions (e.g., rainfall rates), and can be a function of the time interval since contamination. Estimating contamination values of soil for calculations of ingestion requires care. In particular, soil which is contaminated with transuranic radioactivity may be far from homogeneous with respect to contamination, as has been shown in an number of environments including near Chernobyl (Akopova et al. 1991), at the British test site at Maralinga, Australia (Ellis and Wall 1982), and on islands in the Republic of the Marshall Islands (Simon et al. 1995). The presence of hot particles, as noted in these studies, implies that small volumes of soil may vary dramatically in their level of radioactivity, from nearly zero to quite high values. When ingestion rates are relatively small (a few mg d^{-1}), ascertaining the correct contamination level may be extremely difficult and may be best represented by a joint statistical distribution describing the specific activity of hot particles and their spatial frequency in the environment. It is also important to recognize that soil that is intentionally consumed is often taken from deeper soil layers than those that might be readily contaminated. This would mainly apply to adults; children who intentionally eat dirt while at play may be an important exception to this rule.
- Most literature that have reported positive values of soil ingestion are probably either observations of unusual episodic events, e.g., an individual with intestinal blockage (by soil) who reports for medical care, or in studies in which the observation times are relatively short. One of the longer studies conducted was for a 2-wk period (Calabrese et al. 1989), but this may be an inadequate period to observe rare occurrences of geophagia and to determine an appropriate time-averaged intake rate.
- Seasonal variation may be relevant to the occurrence of either inadvertent or intentional soil ingestion. The combination of average climatic conditions of a site and the particular precipitation and temperature conditions of a specific season or year will influence the frequency and degree of soil ingestion among a population or worker group.
- The effects of tradition and culturally bound practices (i.e., ceremonial or religious practices) will influence the distribution of ingestion rates within a population and among indigenous populations in unknown ways.
- A central issue for performing dose assessments for soil intake is the choice of appropriate values for intake rates and how to apply them in the dose calculations. What are relevant ingestion rates may depend on whether the concept of critical group is used and how that group is defined. How soil ingestion rates should be used will primarily depend on how the parameter has been defined (i.e., long-term average, episodic value, etc.) and the assumptions that are inherent in the definition. At this point in time, intake rates cannot be predicted *a priori* for different nationalities, socioeconomic, or ethnic groups, although the literature overwhelmingly cites more evidence of intentional intake among disadvantaged socioeconomic groups and inadvertent intake in primitive living situations.
- The degree of realism or conservatism that is desired in the dose assessment is another important consideration. In some models, the incremental dose added by soil ingestion may be significantly smaller than the uncertainty or variability in the main dose pathways. Thus, consideration must be given as to whether modeling minor routes of exposure is justified. In other cases where the soil ingestion rates are high (e.g., Haywood and Smith 1992), soil ingestion is an important consideration that would leave the assessment considerably in error if it were overlooked.
- Consideration needs to be given to determining the appropriate proportion of the population that is at risk for either inadvertent or intentional soil ingestion. The factor specifying the proportion at risk may be applied in two different ways. First, in collective exposure calculations, the proportion at risk can be used directly to obtain a component of the population collective exposure. In dose assessments for individuals living in a contaminated environment, the proportion may be interpreted as the likelihood of geophagia occurring. The fact that soil ingestion occurs inadvertently may be a

sufficient argument alone for including soil ingestion in more routine calculations of radiation dose to populations living on, or near to, contaminated lands.

- Determining the applicability of published ingestion-rate data is difficult, and making appropriate assumptions concerning ingestion in the face of little data requires careful consideration and subjective judgment. For example, there are few data on ingestion rates for adults under normal conditions (Finley et al. 1994). This problem is even greater for many populations that are poorly studied or understood by western scientists, e.g., indigenous populations.

CONCLUSIONS

There is an abundance of literature confirming that soil ingestion is a worldwide, and, in some locations, relatively commonplace practice or occurrence. The phenomena of inadvertent and intentional intake may take place for many different reasons. Certainly, each of the two phenomenon have unique considerations when attempting to model annual or episodic intake. Moreover, a different set of parameter values is required for every unique combination of environmental and cultural attributes.

Environmental radioactivity released in accidents, e.g., from the Chernobyl reactor, sometimes crosses international borders and may affect populations of different nationalities, environments, economic conditions, lifestyles, and local customs. Thus, using geographic and cultural-specific intake rates as well as properly characterizing variability among individuals within the same group is important for credible risk assessments.

Other health concerns aside, the question remains open whether these instances of intake are truly important to radiation dose assessment questions. Certainly, pre-assessment screening for each dose assessment study should be carried out to determine relevant pathways. In such situations, use of improper parameter values for the population of interest should be guarded against to prevent deriving false-negative conclusions that the pathway is unimportant. As in all dose assessment activities, considerable deliberation and study may be required to determine useful and relevant parameters to properly characterize soil ingestion and the radioactivity concentrations in soil available to persons who might ingest soil.

A number of unresolved issues have been identified that require further study to properly elucidate the importance of soil ingestion to different exposure situations. However, even if additional information is not forthcoming, the potential dose (and risk) due to ingestion of contaminated soil ought to be examined in instances where exposure to environmental radioactivity has taken place.

In environmental radiation dose assessments, soil ingestion will likely be of greatest importance where there is contamination of the soil with actinides or transuranic radionuclides, particularly in those situations encompassing rural, economically poor or undeveloped areas, dry climates, and those societies without commercial agriculture and public water supplies and where indigenous peoples reside.

Of the two types of soil ingestion, inadvertent would affect the greatest number of persons while geophagia would result in the highest intakes for certain individuals. Inadvertent ingestion is most likely correlated in western societies with children's mouthing behaviors and with certain occupations that bring workers into contact with soil, e.g., agriculture, construction, etc. Geophagic behavior seems mainly to occur among pregnant women and children and within both indigenous and non-indigenous peoples. It is of special concern that the life-stages of adolescence, pregnancy, and lactation are those in which purposeful soil ingestion is the most widely documented. Intakes among indigenous people, specifically those living in primitive living conditions and having unusual ceremonial and belief based activities, are probably the poorest understood of all these phenomena.

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