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5. SOIL AND DUST INGESTION

5.1. INTRODUCTION

The ingestion of soil and dust is a potential route of exposure for both adults and children to environmental chemicals. Children, in particular, may ingest significant quantities of soil due to their tendency to play on the floor indoors and on the ground outdoors and their tendency to mouth objects or their hands. Children may ingest soil and dust through deliberate hand-to-mouth movements, or unintentionally by eating food that has dropped on the floor. Adults may also ingest soil or dust particles that adhere to food, cigarettes, or their hands. Thus, understanding soil and dust ingestion patterns is an important part of estimating overall exposures to environmental chemicals.

At this point in time, knowledge of soil and dust ingestion patterns within the United States is somewhat limited. Only a few researchers have attempted to quantify soil and dust ingestion patterns in U.S. adults or children.

This chapter explains the concepts of soil ingestion, soil pica, and geophagy, defines these terms for the purpose of this handbook's exposure factors, and presents available data from the literature on the amount of soil and dust ingested.

The Centers for Disease Control and Prevention's Agency for Toxic Substances and Disease Registry (ATSDR) held a workshop in June 2000 in which a panel of soil ingestion experts developed definitions for soil ingestion, soil-pica, and geophagy, to distinguish aspects of soil ingestion patterns that are important from a research perspective (ATSDR, 2001). This chapter uses the definitions that are based on those developed by participants in that workshop:

Soil ingestion is the consumption of soil. This may result from various behaviors including, but not limited to, mouthing, contacting dirty hands, eating dropped food, or consuming soil directly.

Soil-pica is the recurrent ingestion of unusually high amounts of soil (i.e., on the order of 1,000−5,000 mg/day or more).

Geophagy is the intentional ingestion of earths and is usually associated with cultural practices.

Some studies are of a behavior known as "pica," and the subset of "pica" that consists of ingesting soil. A general definition of the concept of pica is that of ingesting non-food substances, or ingesting large quantities of certain particular foods. Definitions of pica often include references to recurring or repeated ingestion of these substances. Soil-pica is specific to ingesting materials that are defined as soil, such as clays, yard soil, and flower-pot soil. Although soil-pica is a fairly common behavior among children, information about the prevalence of pica behavior is limited. Gavrelis et al. (2011) reported that the prevalence of non-food substance consumption varies by age, race, and income level. The behavior was most prevalent among children 1 to <3 years (Gavrelis et al., 2011). Geophagy, on the other hand, is an extremely rare behavior, especially among children, as is soil-pica among adults. One distinction between geophagy and soil-pica that may have public health implications is the fact that surface soils generally are not the main source of geophagy materials. Instead, geophagy is typically the consumption of clay from known, uncontaminated sources, whereas soil-pica involves the consumption of surface soils, usually the top 2−3 inches (ATSDR, 2001).

Researchers in many different disciplines have hypothesized motivations for human soil-pica or geophagy behavior, including alleviating nutritional deficiencies, a desire to remove toxins or self-medicate, and other physiological or cultural influences (Danford, 1982). Bruhn and Pangborn (1971) and Harris and Harper (1997) suggest a religious context for certain geophagy or soil ingestion practices. Geophagy is characterized as an intentional behavior, whereas soil-pica should not be limited to intentional soil ingestion, primarily because children can consume large amounts of soil from their typical behaviors and because differentiating intentional and unintentional behavior in young children is difficult (ATSDR, 2001). Some researchers have investigated populations that may be more likely than others to exhibit soil-pica or geophagy behavior on a recurring basis. These populations might include pregnant women who exhibit soil-pica behavior (Simpson et al., 2000), adults and children who practice geophagy (Vermeer and Frate, 1979), institutionalized children (Wong, 1988), and children with developmental delays (Danford, 1983), autism (Kinnell, 1985), or celiac disease (Korman, 1990). However, identifying specific soil-pica and geophagy populations remains difficult due to limited research on this topic. It has been estimated that 33% of children ingest more than 10 grams of soil 1 or 2 days a year (ATSDR, 2001). No information was located regarding the prevalence of geophagy behavior.

Because some soil and dust ingestion may be a result of hand-to-mouth behavior, soil properties may be important. For example, soil particle size, organic matter content, moisture content, and other soil properties may affect the adherence of soil to the skin. Soil particle sizes range from 50−2,000 μm for sand, 2−50 μm for silt, and are <2 μm for clay (USDA, 1999), while typical atmospheric dust particle sizes are in the range of 0.001−30 μm (Mody and Jakhete, 1987). Studies on particle size have indicated that finer soil particles (generally <63 μm in diameter) tend to be adhered more efficiently to human hands, whereas adhered soil fractions are independent of organic matter content or soil origin (Choate et al., 2006; Yamamoto et al., 2006). More large particle soil fractions have been shown to adhere to the skin for soils with higher moisture content (Choate et al., 2006).

In this handbook, soil, indoor settled dust and outdoor settled dust are defined generally as the following:

Soil. Particles of unconsolidated mineral and/or organic matter from the earth's surface that are located outdoors, or are used indoors to support plant growth. It includes particles that have settled onto outdoor objects and surfaces (outdoor settled dust).

Indoor Settled Dust. Particles in building interiors that have settled onto objects, surfaces, floors, and carpeting. These particles may include soil particles that have been tracked or blown into the indoor environment from outdoors as well as organic matter.

Outdoor Settled Dust. Particles that have settled onto outdoor objects and surfaces due to either wet or dry deposition. Note that it may not be possible to distinguish between soil and outdoor settled dust, since outdoor settled dust generally would be present on the uppermost surface layer of soil.

For the purposes of this handbook, soil ingestion includes both soil and outdoor settled dust, and dust ingestion includes indoor settled dust only.

There are several methodologies represented in the literature related to soil and dust ingestion. Two methodologies combine biomarker measurements with measurements of the biomarker substance's presence in environmental media. An additional methodology offers modeled estimates of soil/dust ingestion from activity pattern data from observational studies (e.g., videography) or from the responses to survey questionnaires about children's activities, behaviors, and locations.

The first of the biomarker methodologies measures quantities of specific elements present in feces, urine, food and medications, yard soil, house dust, and sometimes also community soil and dust, and combines this information using certain assumptions about the elements' behavior in the gastrointestinal tract to produce estimates of soil and dust quantities ingested (Davis et al., 1990). In this chapter, this methodology is referred to as the "tracer element" methodology. The second biomarker methodology compares results from a biokinetic model of lead exposure and uptake that predict blood lead levels, with biomarker measurements of lead in blood (Von Lindern et al., 2003). The model predictions are made using assumptions about ingested soil and dust quantities that are based, in part, on results from early versions of the first methodology. Therefore, the comparison with actual measured blood lead levels serves to confirm, to some extent, the assumptions about ingested soil and dust quantities used in the biokinetic model. In this chapter, this methodology is referred to as the "biokinetic model comparison" methodology. Lead isotope ratios have also been used as a biomarker to study sources of lead exposures in children. This technique involves measurements of different lead isotopes in blood and/or urine, food, water, and house dust and compares the ratio of different lead isotopes to infer sources of lead exposure that may include dust or other environmental exposures (Manton et al., 2000). However, application of lead isotope ratios to derive estimates of dust ingestion by children has not been attempted. Therefore, it is not discussed any further in this chapter.

The third, "activity pattern" methodology, combines information from hand-to-mouth and object-to-mouth behaviors with microenvironment data (i.e., time spent at different locations) to derive estimates of soil and dust ingestion. Behavioral information often comes from data obtained using videography techniques or from responses to survey questions obtained from adults, caregivers, and/or children. Surveys often include questions about hand-to-mouth and object-to-mouth behaviors, soil and dust ingestion behaviors, frequency, and sometimes quantity (Barltrop, 1966).

Although not directly evaluated in this chapter, a fourth methodology uses assumptions regarding ingested quantities of soil and dust that are based on a general knowledge of human behavior, and potentially supplemented or informed by data from other methodologies (Wong et al., 2000; Kissel et al., 1998; Hawley, 1985).

The recommendations for soil, dust, and soil + dust ingestion rates are provided in the next section, along with a summary of the confidence ratings for these recommendations. The recommended values are based on key studies identified by the U.S. Environmental Protection Agency (U.S. EPA) for this factor. Following the recommendations, a description of the three methodologies used to estimate soil and dust ingestion is provided, followed by a summary of key and relevant studies. Because strengths and limitations of each one of the key and relevant studies relate to the strengths and limitations inherent of the methodologies themselves, they are discussed at the end of the key and relevant studies.

5.2. RECOMMENDATIONS

The key studies described in Section 5.3 were used to recommend values for soil and dust ingestion for adults and children. Table 5-1 shows the central tendency recommendations for daily ingestion of soil, dust, or soil + dust, in mg/day. It also shows the high end recommendations for daily ingestion of soil, in mg/day. The high end recommendations are subdivided into a general population soil ingestion rate, an ingestion rate for "soil-pica," and an estimate for individuals who exhibit "geophagy." The soil pica and geophagy recommendations are likely to represent an acute high soil ingestion episode or behaviors at an unknown point on the high end of the distribution of soil ingestion. Published estimates from the key studies have been rounded to one significant figure.

The soil ingestion recommendations in Table 5-1 are intended to represent ingestion of a combination of soil and outdoor settled dust, without distinguishing between these two sources. The source of the soil in these recommendations could be outdoor soil, indoor containerized soil used to support growth of indoor plants, or a combination of both outdoor soil and containerized indoor soil. The inhalation and subsequent swallowing of soil particles is accounted for in these recommended values, therefore, this pathway does not need to be considered separately. These recommendations are called "soil." The dust ingestion recommendations in Table 5-1 include soil tracked into the indoor setting, indoor settled dust, and air-suspended particulate matter that is inhaled and swallowed. Central tendency "dust" recommendations are provided, in the event that assessors need recommendations for an indoor or inside a transportation vehicle scenario in which dust, but not outdoor soil, is the exposure medium of concern. The soil + dust recommendations would include soil, either from outdoor or containerized indoor sources, dust that is a combination of outdoor settled dust, indoor settled dust, and air-suspended particulate matter that is inhaled, subsequently trapped in mucous and moved from the respiratory system to the gastrointestinal tract, and a soil-origin material located on indoor floor surfaces that was tracked indoors by building occupants. Soil and dust recommendations exclude the soil or dust's moisture content. In other words, recommended values represent mass of ingested soil or dust that is represented on a dry-weight basis.

Studies estimating adult soil ingestion are extremely limited, and only two of these are considered to be key studies [i.e., Vermeer and Frate (1979); Davis and Mirick (2006)]. In the Davis and Mirick (2006) study, soil ingestion for adults and children in the same family was calculated using a mass-balance approach. The adult data were seen to be more variable than for the children in the study, possibly indicating an important occupational contribution of soil ingestion in some of the adults. For the aluminum and silicon tracers, soil ingestion rates ranged from 23−92 mg/day (mean), 0−23 mg/day (median), and 138−814 mg/day (maximum), with an overall mean value of 52 mg/day for the adults in the study. Based on this value, the recommended mean value from the Davis and Mirick (2006) study is estimated to be 50 mg/day for adult soil and dust ingestion (see Table 5-1). There are no available studies estimating the ingestion of dust by adults, therefore, the assumption used by U.S. EPA's Integrated Exposure and Uptake Biokinetic (IEUBK) model for lead in children (i.e., 45% soil, 55% dust contribution) was used to derive estimates for soil and dust using the soil + dust value derived from Davis and Mirick (2006). Rounded to one significant figure, these estimates are 20 mg/day and 30 mg/day for soil and dust respectively.

The key studies pre-dated the age groups recommended for children by U.S. EPA (2005) and were performed on groups of children of varying ages. As a result, central tendency recommendations can be used for the life stage categories of 6 to <12 months, 1 to <2 years, 2 to <3 years, 3 to <6 years, and part of the 6 to <11 years categories. Upper percentile recommendations can be used for the life stage categories of 1 to <2 years, 2 to <3 years, 3 to <6 years, 6 to <11 years, and part or all of the 11 to <16 years category.

The recommended central tendency soil + dust ingestion estimate for infants from 6 weeks up to their first birthday is 60 mg/day (Hogan et al., 1998; van Wijnen et al., 1990). If an estimate is needed for soil only, from soil derived from outdoor or indoor sources, or both outdoor and indoor sources, the recommendation is 30 mg/day (van Wijnen et al., 1990). If an estimate for indoor dust only is needed, that would include a certain quantity of tracked-in soil from outside, the recommendation is 30 mg/day (Hogan et al., 1998). This dust ingestion value is based on the 30 mg/day value for soil ingestion for this age group (van Wijnen et al., 1990), and the assumption that the soil and dust inhalation values will be comparable, as were the Hogan et al. (1998) values for the 1 to <6 year age group. The confidence rating for this recommendation is low due to the small numbers of study subjects in the IEUBK model study on which the recommendation is in part based and the inferences needed to develop a quantitative estimate. Examples of these inferences include: an assumption that the relative proportions of soil and dust ingested by 6 week to <12 month old children are the same as those ingested by older children [45% soil, 55% dust, based on U.S. EPA (1994a)], and the assumption that pre-natal or non-soil, non-dust sources of lead exposure do not dominate these children's blood lead levels.

When assessing risks for individuals who are not expected to exhibit soil-pica or geophagy behavior, the recommended central tendency soil + dust ingestion estimate is 100 mg/day for children ages 1 to <21 years (Hogan et al., 1998). If an estimate for soil only is needed, for exposure to soil such as manufactured topsoil or potted-plant soil that could occur in either an indoor or outdoor setting, or when the risk assessment is not considering children's ingestion of indoor dust (in an indoor setting) as well, the recommendation is 50 mg/day (Hogan et al., 1998). If an estimate for indoor dust only is needed, the recommendation is 60 mg/day (Hogan et al., 1998). Although these quantities add up to 110 mg/day, the sum is rounded to one significant figure. Although there were no tracer element studies or biokinetic model comparison studies performed for children 6 to <21 years, as a group, their mean or central tendency soil ingestion would not be zero. In the absence of data that can be used to develop specific central tendency soil and dust ingestion recommendations for children aged 6 to <11 years, 11 to <16 years and 16 to <21 years, U.S. EPA recommends using the same central tendency soil and dust ingestion rates that are recommended for children in the 1 to <6 year old age range.

No key studies are available estimating soil-pica behavior in children less than 12 months of age or in adults, therefore, no recommended values are provided for these age groups. The upper percentile recommendation for soil and dust ingestion among the general population of children 3 to <6 years old is 200 mg/day and it is based on the 95th percentile value obtained from modeling efforts from Özkaynak et al. (2011) and from 95th percentile estimates derived by Stanek and Calabrese (1995b). When assessing risks for children who may exhibit soil-pica behavior, or a group of children that includes individual children who may exhibit soil-pica behavior, the soil-pica ingestion estimate in the literature for children up to age 14 ranges from 400 to 41,000 mg/day (Stanek et al., 1998; Calabrese et al., 1997b; Calabrese et al., 1997a; Calabrese and Stanek, 1993; Calabrese et al., 1991; Barnes, 1990; Calabrese et al., 1989; Wong, 1988; Vermeer and Frate, 1979). Due to the definition of soil-pica used in this chapter, that sets a lower bound on the quantity referred to as "soil-pica" at 1,000 mg/day (ATSDR, 2001), and due to the significant number of observations in the U.S. tracer element studies that are at or exceed that quantity, the recommended soil-pica ingestion rate is 1,000 mg/day. It should be noted, however, that this value may be more appropriate for acute exposures. Currently, no data are available for soil-pica behavior for children ages 6 to <21 years. Because pica behavior may occur among some children ages ~1 to 21 years old (Hyman et al., 1990), it is prudent to assume that, for some children, soil-pica behavior may occur at any age up to 21 years.

The recommended geophagy soil estimate is 50,000 mg/day (50 grams) for both adults and children (Vermeer and Frate, 1979). It is important to note that this value may be more representative of acute exposures. Risk assessors should use this value for soil ingestion in areas where residents are known to exhibit geophagy behaviors.

Table 5-2 shows the confidence ratings for these recommendations. Section 5.4 gives a more detailed explanation of the basis for the confidence ratings.

An important factor to consider when using these recommendations is that they are limited to estimates of soil and dust quantities ingested. The scope of this chapter is limited to quantities of soil and dust taken into the gastrointestinal tract, and does not extend to issues regarding bioavailability of environmental contaminants present in that soil and dust. Information from other sources is needed to address bioavailability. In addition, as more information becomes available regarding gastrointestinal absorption of environmental contaminants, adjustments to the soil and dust ingestion exposure equations may need to be made, to better represent the direction of movement of those contaminants within the gastrointestinal tract.

To place these recommendations into context, it is useful to compare these soil ingestion rates to common measurements. The central tendency recommendation of 50 mg/day or 0.050 g/day, dry-weight basis, would be equivalent to approximately 1/6 of an aspirin tablet per day because the average aspirin tablet is approximately 325 mg. The 50 g/day ingestion rate recommended to represent geophagy behavior would be roughly equivalent to 150 aspirin tablets per day.

Table 5-1. Recommended Values for Daily Soil, Dust, and Soil + Dust Ingestion (mg/day)

	Soil[a]				Dust[b]		Soil + Dust	
		High End						
Age Group	General Population Central Tendency[c]	General Population Upper Percentile[d]	Soil-Pica[e]	Geophagy[f]	General Population Central Tendency[g]	General Population Upper Percentile[h]	General Population Central Tendency[c]	General Population Upper Percentile[h]
6 weeks to <1 year	30				30		60	
1 to <6 years	50		1,000	50,000	60		100[i]	
3 to <6 years		200				100		200
6 to <21 years	50		1,000	50,000	60		100[i]	
Adult	20[j]			50,000	30[j]		50	

a Includes soil and outdoor settled dust.
b Includes indoor settled dust only.
c Davis and Mirick (2006); Hogan et al. (1998); Davis et al. (1990); van Wïjnen et al. (1990); Calabrese and Stanek (1995).
d Özkaynak et al. (2011); Stanek and Calabrese (1995b); rounded to one significant figure.
e ATSDR (2001); Stanek et al. (1998); Calabrese et al. (1997b; 1997a; 1991; 1989); Calabrese and Stanek (1993); Barnes (1990); Wong (1988); Vermeer and Frate (1979).
f Vermeer and Frate (1979).
g Hogan et al. (1998).
h Özkaynak et al. (2011); rounded to one significant figure.
i Total soil and dust ingestion rate is 110 mg/day; rounded to one significant figure it is 100 mg/day.
j Estimates of soil and dust were derived from the soil + dust and assuming 45% soil and 55% dust.

Table 5-2. Confidence in Recommendations for Ingestion of Soil and Dust

General Assessment Factors	Rationale	Rating
Soundness		Low
Adequacy of Approach	The methodologies have significant limitations. The studies did not capture all of the information needed (quantities ingested, frequency of high soil ingestion episodes, prevalence of high soil ingestion). Six of the 12 key studies were of census or randomized design. Sample selection may have introduced some bias in the results (i.e., children near smelter or Superfund sites, volunteers in nursery schools). The total number of adults and children in key studies were 122 and 1,203 (859 U.S. children, 292 Dutch, and 52 Jamaican children), respectively, while the target population currently numbers more than 74 million (U.S. Department of Commerce, 2008). Modeled estimates were based on 1,000 simulated individuals. The response rates for in-person interviews and telephone surveys were often not stated in published articles. Primary data were collected for 381 U.S. children and 292 Dutch children; secondary data for 478 U.S. children and 52 Jamaican children. Two key studies provided data for adults.	
Minimal (or defined) Bias	Numerous sources of measurement error exist in the tracer element studies. Biokinetic model comparison studies may contain less measurement error than tracer element studies. Survey response study may contain measurement error. Some input variables for the modeled estimates are uncertain.	
Applicability and Utility		Low
Exposure Factor of Interest	Eleven of the 12 key studies focused on the soil exposure factor, with no or less focus on the dust exposure factor. The biokinetic model comparison study did not focus exclusively on soil and dust exposure factors.	
Representativeness	The study samples may not be representative of the United States in terms of race, ethnicity, socioeconomics, and geographical location; studies focused on specific areas.	
Currency	Studies results are likely to represent current conditions.	
Data Collection Period	Tracer element studies' data collection periods may not represent long-term behaviors. Biokinetic model comparison and survey response studies do represent longer term behaviors. Data used in modeled simulation estimates may not represent long-term behaviors.	
Clarity and Completeness		Low
Accessibility	Observations for individual children are available for only three of the 12 key studies.	
Reproducibility	For the methodologies used by more than one research group, reproducible results were obtained in some instances. Some methodologies have been used by only one research group and have not been reproduced by others.	
Quality Assurance	For some studies, information on quality assurance/quality control was limited or absent.	
Variability and Uncertainty		Low
Variability in Population	Tracer element and activity pattern methodology studies characterized variability among study sample members; biokinetic model comparison and survey response studies did not. Day-to-day and seasonal variability was not very well characterized. Numerous factors that may influence variability have not been explored in detail.	
Minimal Uncertainty	Estimates are highly uncertain. Tracer element studies' design appears to introduce biases in the results. Modeled estimates may be sensitive to input variables.	
Evaluation and Review		Medium
Peer Review	All key studies appeared in peer-review journals.	
Number and Agreement of Studies	12 key studies. Some key studies are reanalysis of previously published data. Researchers using similar methodologies obtained generally similar results; somewhat general agreement between researchers using different methodologies.	
Overall Rating		**Low**

5.3. KEY AND RELEVANT STUDIES

The key tracer element, biokinetic model comparison, and survey response studies are summarized in the following sections. Certain studies were considered "key" and were used as a basis for developing the recommendations, using judgment about the study's design features, applicability, and utility of the data to U.S. soil and dust ingestion rates, clarity and completeness, and characterization of uncertainty and variability in ingestion estimates. Because the studies often were performed for reasons unrelated to developing soil and dust ingestion recommendations, their attributes that were characterized as "limitations" in this chapter might not be limitations when viewed in the context of the study's original purpose. However, when studies are used for developing a soil or dust ingestion recommendation, U.S. EPA has categorized some studies' design or implementation as preferable to others. In general, U.S. EPA chose studies designed either with a census or randomized sample approach over studies that used a convenience sample, or other non-randomized approach, as well as studies that more clearly explained various factors in the study's implementation that affect interpretation of the results. However, in some cases, studies that used a non-randomized design contain information that is useful for developing exposure factor recommendations (for example, if they are the only studies of children in a particular age category), and thus may have been designated as "key" studies. Other studies were considered "relevant" but not "key" because they provide useful information for evaluating the reasonableness of the data in the key studies, but in U.S. EPA's judgment they did not meet the same level of soundness, applicability and utility, clarity and completeness, and characterization of uncertainty and variability that the key studies did. In addition, studies that did not contain information that can be used to develop a specific recommendation for mg/day soil and dust ingestion were classified as relevant rather than key.

Some studies are re-analyses of previously published data. For this reason, the sections that follow are organized into key and relevant studies of primary analysis (that is, studies in which researchers have developed primary data pertaining to soil and dust ingestion) and key and relevant studies of secondary analysis (that is, studies in which researchers have interpreted previously published results, or data that were originally collected for a different purpose).

5.3.1. Methodologies Used in Key Studies

5.3.1.1. *Tracer Element Methodology*

The tracer element methodology attempts to quantify the amounts of soil ingested by analyzing samples of soil and dust from residences and/or children's play areas, and feces or urine. The soil, dust, fecal, and urine samples are analyzed for the presence and quantity of tracer elements—typically, aluminum, silicon, titanium, and other elements. A key underlying assumption is that these elements are not metabolized into other substances in the body or absorbed from the gastrointestinal tract in significant quantities, and thus their presence in feces and urine can be used to estimate the quantity of soil ingested by mouth. Although they are sometimes called mass balance studies, none of the studies attempt to quantify amounts excreted in perspiration, tears, glandular secretions, or shed skin, hair or finger- and toenails, nor do they account for tracer element exposure via the dermal or inhalation into the lung routes, and thus they are not a complete "mass balance" methodology. Early studies using this methodology did not always account for the contribution of tracer elements from non-soil substances (food, medications, and non-food sources such as toothpaste) that might be swallowed. U.S. studies using this methodology in or after the mid to late 1980s account for, or attempt to account for, tracer element contributions from these non-soil sources. Some study authors adjust their soil ingestion estimate results to account for the potential contribution of tracer elements found in household dust as well as soil.

The general algorithm that is used to calculate the quantity of soil or dust estimated to have been ingested is as follows: the quantity of a given tracer element, in milligrams, present in the feces and urine, minus the quantity of that tracer element, in milligrams, present in the food and medicine, the result of which is divided by the tracer element's soil or dust concentration, in milligrams of tracer per gram of soil or dust, to yield an estimate of ingested soil, in grams.

The U.S. tracer element researchers have all assumed a certain offset, or lag time between ingestion of food, medication, and soil, and the resulting fecal and urinary output. The lag times used are typically 24 or 28 hours; thus, these researchers subtract the previous day's food and medication tracer element quantity ingested from the current day's fecal and urinary tracer element quantity that was excreted. When compositing food, medication, fecal and urine samples across the entire study period, daily estimates can be obtained by dividing the total estimated soil ingestion by the number of days in which fecal and/or urine samples were collected. A variation of the algorithm that provides slightly higher estimates of soil ingestion is to divide the total estimated soil ingestion by the number of days on which feces were produced, which by definition would be equal to or less than the total number of days of the study period's fecal sample collection.

Substituting tracer element dust concentrations for tracer element soil concentrations yields a dust ingestion estimate. Because the actual non-food, non-medication quantity ingested is a combination of soil and dust, the unknown true soil and dust ingestion is likely to be somewhere between the estimates that are based on soil concentrations and estimates that are based on dust concentrations. Tracer element researchers have described ingestion estimates for soil that actually represent a combination of soil and dust, but were calculated based on tracer element concentrations in soil. Similarly, they have described ingestion estimates for dust that are actually for a combination of soil and dust, but were calculated based on tracer element concentrations in dust. Other variations on these general soil and dust ingestion algorithms have been published, in attempts to account for time spent indoors, time spent away from the house, etc. that could be expected to influence the relative proportion of soil versus dust.

Each individual's soil and dust ingestion can be represented as an unknown constant in a set of simultaneous equations of soil or dust ingestion represented by different tracer elements. To date, only two of the U.S. research teams (Barnes, 1990; Lásztity et al., 1989) have published estimates calculated for pairs of tracer elements using simultaneous equations.

The U.S. tracer element studies have been performed for only short-duration study periods, and only for 33 adults (Davis and Mirick, 2006) and 241 children [101 in Davis et al. (1990), 12 of whom were studied again in Davis and Mirick (2006); 64 in Calabrese et al. (1989) and Barnes (1990); 64 in Calabrese et al. (1997b); and 12 in Calabrese et al. (1997a)]. They provide information on quantities of soil and dust ingested for the studied groups for short time periods, but provide limited information on overall prevalence of soil ingestion by U.S. adults and children, and limited information on the frequency of higher soil ingestion episodes.

The tracer element studies appear to contain numerous sources of error that influence the estimates upward and downward. Sometimes the error sources cause individual soil or dust ingestion estimates to be negative, which is not physically possible. In some studies, for some of the tracers, so many individual "mass balance" soil ingestion estimates were negative that median or mean estimates based on that tracer were negative. For soil and dust ingestion estimates based on each particular tracer, or averaged across tracers, the net impact of these competing upward and downward sources of error is unclear.

5.3.1.2. *Biokinetic Model Comparison Methodology*

The Biokinetic Model Comparison methodology compares direct measurements of a biomarker, such as blood or urine levels of a toxicant, with predictions from a biokinetic model of oral, dermal and inhalation exposure routes with air, food, water, soil, and dust toxicant sources. An example is to compare measured children's blood lead levels with predictions from the IEUBK model. Where environmental contamination of lead in soil, dust, and drinking water has been measured and those measurements can be used as model inputs for the children in a specific community, the model's assumed soil and dust ingestion values can be confirmed or refuted by comparing the model's predictions of blood lead levels with those children's measured blood lead levels. It should be noted, however, that such confirmation of the predicted blood lead levels would be confirmation of the net impact of all model inputs, and not just soil and dust ingestions. Under the assumption that the actual measured blood lead levels of various groups of children studied have minimal error, and those measured blood lead levels roughly match biokinetic model predictions for those groups of children, then the model's default assumptions may be roughly accurate for the central tendency, or typical, children in an assessed group of children. The model's default assumptions likely are not as useful for predicting outcomes for highly exposed children.

5.3.1.3. *Activity Pattern Methodology*

The activity pattern methodology includes observational studies as well as surveys of adults, children's caretakers, or children themselves, via in-person or mailed questionnaires that ask about mouthing behavior and ingestion of various non-food items and time spent in various microenvironments. There are three general approaches to gather data on children's mouthing behavior: real-time hand recording, in which trained observers manually record information (Davis et al., 1995); video-transcription, in which trained videographers tape a child's activities and subsequently extract the pertinent data manually or with computer software (Black et al., 2005); and questionnaire, or survey response, techniques (Stanek et al., 1998).

The activity-pattern methodology combines information on hand-to-mouth and object-to-mouth activities (microactivities) and time spent at various locations (microenvironments) with assumptions about transfer parameters (e.g., soil-to-skin adherence, saliva removal efficiency) and other exposure factors (e.g., frequency of hand washing) to derive estimates of soil and dust ingestion. This methodology has been used in U.S. EPA's Stochastic Human Exposure and Dose Simulation (SHEDS) model. The SHEDS model is a probabilistic model that can simulate cumulative (multiple chemicals) or aggregate (single chemical) residential exposures for a population of interest over time via multiple routes of exposure for different types of chemicals and scenarios, including those involving soil ingestion (U.S. EPA, 2010).

One of the limitations of this approach includes the availability and quality of the input variables. Özkaynak et al. (2011) found that the model is most sensitive to dust loadings on carpets and hard floor surfaces, soil-to-skin adherence factors, hand mouthing frequency, and hand washing frequency (Ozkaynak et al., 2011).

5.3.2. Key Studies of Primary Analysis

5.3.2.1. *Vermeer and Frate (1979)—Geophagia in Rural Mississippi: Environmental and Cultural Contexts and Nutritional Implications*

Vermeer and Frate (1979) performed a survey response study in Holmes County, Mississippi in the 1970s (date unspecified). Questions about geophagy (defined as regular consumption of clay over a period of weeks) were asked of household members (N = 229 in 50 households; 56 were women, 33 were men, and 140 were children or adolescents) of a subset of a random sample of nutrition survey respondents. Caregiver responses to questions about 115 children under 13 indicate that geophagy was likely to be practiced by a minimum of 18 (16%) of these children; however, 16 of these 18 children were 1 to 4 years old, and only 2 of the 18 were older than 4 years. Of the 56 women, 32 (57%) reported eating clay. There was no reported geophagy among 33 men or 25 adolescent study subjects questioned.

In a separately administered survey, geophagy and pica data were obtained from 142 pregnant women over a period of 10 months. Geophagy was reported by 40 of these women (28%), and an additional 27 respondents (19%) reported other pica behavior, including the consumption of laundry starch, dry powdered milk, and baking soda.

The average daily amount of clay consumed was reported to be about 50 grams, for the adult and child respondents who acknowledged practicing geophagy. Quantities were usually described as either portions or multiples of the amount that could be held in a single, cupped hand. Clays for consumption were generally obtained from the B soil horizon, or subsoil rather than an uppermost layer, at a depth of 50 to 130 centimeters.

5.3.2.2. *Calabrese et al. (1989)—How Much Soil Do Young Children Ingest: An Epidemiologic Study/Barnes (1990)—Childhood Soil Ingestion: How Much Dirt Do Kids Eat?/Calabrese et al. (1991)—Evidence of Soil-Pica Behavior and Quantification of Soil Ingested*

Calabrese et al. (1989) and Barnes (1990) studied soil ingestion among children using eight tracer elements—aluminum, barium, manganese, silicon, titanium, vanadium, yttrium, and zirconium. A non-random sample of 30 male and 34 female 1, 2, and 3-year-olds from the greater Amherst, Massachusetts area were studied, presumably in 1987. The children were predominantly from two-parent households where the parents were highly educated. The study was conducted over a period of 8 days spread over 2 weeks. During each week, duplicate samples of food, beverages, medicines, and vitamins were collected on Monday through Wednesday, while excreta, excluding wipes and toilet paper, were collected for four 24-hour cycles running from Monday/Tuesday through Thursday/Friday. Soil and dust samples were also collected from the child’s home and play area. Study participants were supplied with toothpaste, baby cornstarch, diaper rash cream, and soap with low levels of most of the tracer elements.

Table 5-3 shows the published mean soil ingestion estimates ranging from −294 mg/day based on manganese to 459 mg/day based on vanadium, median soil ingestion estimates ranging from −261 mg/day based on manganese to 96 mg/day based on vanadium, and 95th percentile estimates ranged from 106 mg/day based on yttrium to 1,903 mg/day based on vanadium. Maximum daily soil ingestion estimates ranged from 1,391 mg/day based on zirconium to 7,281 mg/day based on manganese. Dust ingestions calculated using tracer concentrations in dust were often, but not always, higher than soil ingestions calculated using tracer concentrations in soil.

Data for the uppermost 23 subject-weeks (the highest soil ingestion estimates, averaged over the 4 days of excreta collection during each of the 2 weeks) were published in Calabrese et al. (1991). One child's soil-pica behavior was estimated in Barnes (1990) using both the subtraction/division algorithm and the simultaneous equations method. On two particular days during the second week of the study period, the child's aluminum-based soil ingestion estimates were 19 g/day (18,700 mg/day) and 36 g/day (35,600 mg/day), silicon-based soil ingestion estimates were 20 g/day (20,000 mg/day) and 24 g/day (24,000), and simultaneous-equation soil ingestion estimates were 20 g/day (20,100 mg/day) and 23 g/day (23,100 mg/day) (Barnes, 1990). By tracer, averaged across the entire week, this child's estimates ranged from approximately 10 to 14 g/day during the second week of observation [Calabrese et al. (1991), shown in Table 5-4], and averaged 6 g/day across the entire study period. Additional information about this child's apparent ingestion of soil versus dust during the study period was published in Calabrese and Stanek (1992b).

5.3.2.3. *Van Wijnen et al. (1990)—Estimated Soil Ingestion by Children*

In a tracer element study by van Wijnen et al. (1990), soil ingestion among Dutch children ranging in age from 1 to 5 years was evaluated using a tracer element methodology. Van Wijnen et al. (1990) measured three tracers (titanium, aluminum, and acid insoluble residue [AIR]) in soil and feces. The authors estimated soil ingestion based on an assumption called the Limiting Tracer Method (LTM), which assumed that soil ingestion could not be higher than the lowest value of the three tracers. LTM values represented soil ingestion estimates that were not corrected for dietary intake.

An average daily feces dry weight of 15 grams was assumed. A total of 292 children attending daycare centers were studied during the first of two sampling periods and 187 children were studied in the second sampling period; 162 of these children were studied during both periods (i.e., at the beginning and near the end of the summer of 1986). A total of 78 children were studied at campgrounds. The authors reported geometric mean LTM values because soil ingestion rates were found to be skewed and the log-transformed data were approximately normally distributed. Geometric mean LTM values were estimated to be 111 mg/day for children in daycare centers and 174 mg/day for children vacationing at campgrounds (see Table 5-5). For the 162 daycare center children studied during both sampling periods the arithmetic mean LTM was 162 mg/day, and the median was 114 mg/day.

Fifteen hospitalized children were studied and used as a control group. These children's LTM soil ingestion estimates were 74 (geometric mean), 93 (mean), and 110 (median) mg/day. The authors assumed the hospitalized children's soil ingestion estimates represented dietary intake of tracer elements, and used rounded 95% confidence limits on the arithmetic mean, 70 to 120 mg/day, to correct the daycare and campground children's LTM estimates for dietary intake of tracers. Corrected soil ingestion rates were 69 mg/day (162 mg/day minus 93 mg/day) for daycare children and 120 mg/day (213 mg/day minus 93 mg/day) for campers. Corrected geometric mean soil ingestion was estimated to range from 0 to 90 mg/day, with a 90th percentile value of up to 190 mg/day for the various age categories within the daycare group and 30 to 200 mg/day, with a 90th percentile value of up to 300 mg/day for the various age categories within the camping group.

AIR was the limiting tracer in about 80%of the samples. Among children attending daycare centers, soil ingestion was also found to be higher when the weather was good (i.e., <2 days/week precipitation) than when the weather was bad (i.e., >4 days/week precipitation (see Table 5-6).

5.3.2.4. *Davis et al. (1990)—Quantitative Estimates of Soil Ingestion in Normal Children Between the Ages of 2 and 7 Years: Population-Based Estimates Using Aluminum, Silicon, and Titanium as Soil Tracer Elements*

Davis et al. (1990) used a tracer element technique to estimate soil ingestion among children. In this study, 104 children between the ages of 2 and 7 years were randomly selected from a three-city area in southeastern Washington State. Soil and dust ingestion was evaluated by analyzing soil and house dust, feces, urine, and duplicate food, dietary supplement, medication and mouthwash samples for aluminum, silicon, and titanium. Data were collected for 101 of the 104 children during July, August, or September, 1987. In each family, data were collected over a 7-day period, with 4 days of excreta sample collection. Participants were supplied with toothpaste with known tracer element content. In addition, information on dietary habits and demographics was collected in an attempt to identify behavioral and demographic characteristics that influence soil ingestion rates among children. The amount of soil ingested on a daily basis was estimated using Equation 5-1:

$$S_{i,e} = \frac{(((DW_f + DW_p) \times E_f) + 2E_u) - (DW_{fd} \times E_{fd})}{E_{soil}} \quad \text{(Eqn. 5-1)}$$

where:

- $S_{i,e}$ =soil ingested for child *i* based on tracer *e* (grams);
- DW_f =feces dry weight (grams);
- DW_p =feces dry weight on toilet paper (grams);
- E_f =tracer concentration in feces (µg/g);
- E_u =tracer amount in urine (µg);
- DW_{fd} =food dry weight (grams);
- E_{fd} =tracer concentration in food (µg/g); and
- E_{soil} =tracer concentration in soil (µg/g).

The soil ingestion rates were corrected by adding the amount of tracer in vitamins and medications to the amount of tracer in food, and adjusting the food, fecal and urine sample weights to account for missing samples. Food, fecal and urine samples were composited over a 4-day period, and estimates for daily soil ingestion were obtained by dividing the 4-day composited tracer quantities by 4.

Soil ingestion rates were highly variable, especially those based on titanium. Mean daily soil ingestion estimates were 38.9 mg/day for aluminum, 82.4 mg/day for silicon and 245.5 mg/day for titanium (see Table 5-7). Median values were 25 mg/day for aluminum, 59 mg/day for silicon, and 81 mg/day for titanium. The investigators also evaluated the extent to which differences in tracer concentrations in house dust and yard soil impacted estimated soil ingestion rates. The value used in the denominator of the soil ingestion estimate equation was recalculated to represent a weighted average of the tracer concentration in yard soil and house dust based on the proportion of time the child spent indoors and outdoors, using an assumption that the likelihood of ingesting soil outdoors was the same as that of ingesting dust indoors. The adjusted mean soil/dust ingestion rates were 64.5 mg/day for aluminum, 160.0 mg/day for silicon, and 268.4 mg/day for titanium. Adjusted median soil/dust ingestion rates were: 51.8 mg/day for aluminum, 112.4 mg/day for silicon, and 116.6 mg/day for titanium. The authors investigated whether nine behavioral and demographic factors could be used to predict soil ingestion, and found family income less than $15,000/year and swallowing toothpaste to be significant predictors with silicon-based estimates; residing in one of the three cities to be a significant predictor with aluminum-based estimates, and washing the face before eating significant for titanium-based estimates.

5.3.2.5. *Calabrese et al. (1997b)—Soil Ingestion Estimates for Children Residing on a Superfund Site*

Calabrese et al. (1997b) estimated soil ingestion rates for children residing on a Superfund site using a methodology in which eight tracer elements were analyzed. The methodology used in this study is similar to that employed in Calabrese et al. (1989), except that rather than using barium, manganese, and vanadium as three of the eight tracers, the researchers replaced them with cerium, lanthanum, and neodymium. A total of 64 children ages 1−3 years (36 male, 28 female) were selected for this study of the Anaconda, Montana area. The study was conducted for seven consecutive days during September or September and October, apparently in 1992, shortly after soil was removed and replaced in some residential yards in the area. Duplicate samples of meals, beverages, and over-the-counter medicines and vitamins were collected over the 7 day period, along with fecal samples. In addition, soil and dust samples were collected from the children's home and play areas. Toothpaste containing non-detectable levels of the tracer elements, with the exception of silica, was provided to all of the children. Infants were provided with baby cornstarch, diaper rash cream, and soap, which were found to contain low levels of tracer elements.

Because of the high degree of intertracer variability, Calabrese et al. (1997b) also derived estimates based on the "Best Tracer Methodology" (BTM). This BTM uses food/soil tracer concentration ratios in order to correct for errors caused by misalignment of tracer input and outputs, ingestion of non-food sources, and non-soil sources (Stanek and Calabrese, 1995b). A low food/soil ratio is desired because it minimizes transit time errors. The BTM did not use the results from Ce, La, and Nd despite these tracers having low food/soil ratios because the soil concentrations for these elements were found to be affected by particle size and more susceptible to source errors. Calabrese et al. (1997b) noted that estimates based on Al, Si, and Y in this study may result in lower soil ingestion estimates than the true value because the apparent residual negative errors found for these three tracers for a large majority of subjects. It was noted that soil ingestion estimates for this population may be lower than estimates found by previous studies in the literature because of families' awareness of contamination from the Superfund site, which may have resulted in altered behavior.

Soil ingestion estimates were also examined based on various demographic characteristics. There were no statistically significant differences in soil ingestion based on age, sex, birth order, or house yard characteristics (Calabrese et al., 1997b). Although not statistically significant, soil ingestion rates were generally higher for females, children with lower birth number, children with parents employed as laborers, or in service profession, homemakers, or unemployed and for children with pets (Calabrese et al., 1997b).

Table 5-8 shows the estimated soil and dust ingestion by each tracer element and by the BTM. Based on the BTM, the mean soil and dust ingestion rates were 65.5 mg/day and 127.2 mg/day, respectively.

5.3.2.6. *Stanek et al. (1998)—Prevalence of Soil Mouthing/Ingestion Among Healthy Children Aged One to Six/Calabrese et al. (1997a)—Soil Ingestion Rates in Children Identified by Parental Observation as Likely High Soil Ingesters*

Stanek et al. (1998) conducted a survey response study using in-person interviews of parents of children attending well visits at three western Massachusetts medical clinics in August, September, and October of 1992. Of 528 children ages 1 to 7 with completed interviews, parents reported daily mouthing or ingestion of sand and stones in 6%, daily mouthing or ingestion of soil and dirt in 4%, and daily mouthing or ingestion of dust, lint and dustballs in 1%. Parents reported more than weekly mouthing or ingestion of sand and stones in 16%, more than weekly mouthing or ingestion of soil and dirt in 10%, and more than weekly mouthing or ingestion of dust, lint and dustballs in 3%. Parents reported more than monthly mouthing or ingestion of sand and stones in 27%, more than monthly mouthing or ingestion of soil and dirt in 18%, and more than monthly mouthing or ingestion of dust, lint, and dustballs in 6%.

Calabrese and colleagues performed a follow-up tracer element study (Calabrese et al., 1997a) for a subset ($N = 12$) of the Stanek et al. (1998) children whose caregivers had reported daily sand/soil ingestion ($N = 17$). The time frame of the follow-up tracer study relative to the original survey response study was not stated; the study duration was 7 days. Of the 12 children in Calabrese et al. (1997a), one exhibited behavior that the authors believed was clearly soil pica; Table 5-9 shows estimated soil ingestion rates for this child during the study period. Estimates ranged from –10 mg/day to 7,253 mg/day depending on the tracer. Table 5-10 presents the estimated average daily soil ingestion estimates for the 12 children studied. Estimates calculated based on soil tracer element concentrations only ranged from –15 to +1,783 mg/day based on aluminum, −46 to +931 mg/day based on silicon, and –47 to +3,581 mg/day based on titanium. Estimated average daily dust ingestion estimates ranged from −39 to +2,652 mg/day based on aluminum, –351 to +3,145 mg/day based on silicon, and –98 to +3,632 mg/day based on titanium. Calabrese et al. (1997a) question the validity of retrospective caregiver reports of soil pica on the basis of the tracer element results.

5.3.2.7. *Davis and Mirick (2006)—Soil Ingestion in Children and Adults in the Same Family*

Davis and Mirick (2006) calculated soil ingestion for children and adults in the same family using a tracer element approach. Data were collected in 1988, one year after the Davis et al. (1990) study was conducted. Samples were collected and prepared for laboratory analysis and then stored for a 2-year period prior to tracer element quantification with laboratory analysis. Analytical recovery values for spiked samples were within the quality control limits of ±25%. The 20 families in this study were a non-random subset of the 104 families who participated in the soil ingestion study by Davis et al. (1990). Data collection issues resulted in sufficiently complete data for only 19 of the 20 families consisting of a child participant from the Davis et al. (1990) study ages 3 to 7, inclusive, and a female and male parent or guardian living in the same house. Duplicate samples of all food and medication items consumed, and all feces excreted, were collected for 11 consecutive days. Urine samples were collected twice daily for 9 of the 11 days; for the remaining 2 days, attempts were made to collect full 24-hour urine specimens. Soil and house dust samples were also collected. Only 12 children had sufficiently complete data for use in the soil and dust ingestion estimates.

Tracer elements for this study included aluminum, silicon, and titanium. Toothpaste was supplied for use by study participants. In addition, parents completed a daily diary of activities for themselves and the participant child for 4 consecutive days during the study period.

Table 5-11 shows soil ingestion rates for all three family member participants. The mean and median estimates for children for all three tracers ranged from 36.7 to 206.9 mg/day and 26.4 to 46.7 mg/day, respectively, and fall within the range of those reported by Davis et al. (1990). Adult soil ingestion estimates ranged from 23.2 to 624.9 mg/day for mean values and from 0 to 259.5 mg/day for median values. Adult soil ingestion estimates were more variable than those of children in the study regardless of the tracer. The authors believed that this higher variability may have indicated an important occupational contribution of soil ingestion in some, but not all, of the adults. Similar to previous studies, the soil ingestion estimates were the highest for titanium. Although toothpaste is a known source of titanium, the titanium content of the toothpaste used by study participants was not determined.

Only three of a number of behaviors examined for their relationship to soil ingestion were found to be associated with increased soil ingestion in this study:

- reported eating of dirt (for children);
- occupational contact with soil (for adults); and
- hand washing before meals (for both children and adults).

Several typical childhood behaviors, however, including thumb-sucking, furniture licking, and carrying around a blanket or toy were not associated with increased soil ingestion for the participating children. Among both parents and children, neither nail-biting nor eating unwashed fruits or vegetables was correlated with increased soil ingestion. However, because the study design required an equal amount of any food consumed to be included in the sample for analysis, eating unwashed fruits or vegetables would not have contributed to an increase in soil ingestion. Although eating unwashed fruits or vegetables was not associated with soil ingestion in either children or adults in this study, the authors noted that it is a behavior that could lead to soil ingestion. When investigating correlations within the same family, a child's soil ingestion was not found to be associated with either parent's soil ingestion, nor did the mother and father's soil ingestion appear to be correlated.

5.3.3. Key Studies of Secondary Analysis

5.3.3.1. *Wong (1988)—The Role of Environmental and Host Behavioral Factors in Determining Exposure to Infection With Ascaris lumbricoides and Trichuris Trichiura/Calabrese and Stanek (1993)—Soil Pica: Not a Rare Event*

Calabrese and Stanek (1993) reviewed a tracer element study that was conducted by Wong (1988) to estimate the amount of soil ingested by two groups of children. Wong (1988) studied a total of 52 children in two government institutions in Jamaica. The younger group included 24 children with an average age of 3.1 years (range of 0.3 to 7.5 years). The older group included 28 children with an average age of 7.2 years (range of 1.8 to 14 years). One fecal sample was collected each month from each subject over the 4-month study period. The amount of silicon in dry feces was measured to estimate soil ingestion.

An unspecified number of daily fecal samples were collected from a hospital control group of 30 children with an average age of 4.8 years (range of 0.3 to 12 years). Dry feces were observed to contain 1.45% silicon, or 14.5 mg Si per gram of dry feces. This quantity was used to correct measured fecal silicon from dietary sources. Fecal silicon quantities greater than 1.45% in the 52 studied children were interpreted as originating from soil ingestion.

For the 28 children in the older group, soil ingestion was estimated to be 58 mg/day, based on the mean minus one outlier, and 1,520 mg/day, based on the mean of all the children. The outlier was a child with an estimated average soil ingestion rate of 41 g/day over the 4 months.

Estimates of soil ingestion were higher in the younger group of 24 children. The mean soil ingestion of all the children was 470 ± 370 mg/day. Due to some sample losses, of the 24 children studied, only 15 had samples for each of the 4 months of the study. Over the entire 4-month study period, 9 of 84 samples (or 10.5%) yielded soil ingestion estimates in excess of 1 g/day.

Of the 52 children studied, 6 had one-day estimates of more than 1,000 mg/day. Table 5-12 shows the estimated soil ingestion for these six children. The article describes 5 of 24 (or 20.8%) in the younger group of children as having a >1,000 mg/day estimate on at least one of the four study days; in the older group one child is described in this manner. A high degree of daily variability in soil ingestion was observed among these six children; three showed soil-pica behavior on 2, 3, and 4 days, respectively, with the most consistent (4 out of

4 days) soil-pica child having the highest estimated soil ingestion, 3.8 to 60.7 g/day.

5.3.3.2. *Calabrese and Stanek (1995)—Resolving Intertracer Inconsistencies in Soil Ingestion Estimation*

Calabrese and Stanek (1995) explored sources and magnitude of positive and negative errors in soil ingestion estimates for children on a subject-week and trace element basis. Calabrese and Stanek (1995) identified possible sources of positive errors as follows:

- Ingestion of high levels of tracers before the start of the study and low ingestion during the study period; and
- Ingestion of element tracers from a non-food or non-soil source during the study period.

Possible sources of negative bias were identified as follows:

- Ingestion of tracers in food that are not captured in the fecal sample either due to slow lag time or not having a fecal sample available on the final study day; and
- Sample measurement errors that result in diminished detection of fecal tracers, but not in soil tracer levels.

The authors developed an approach that attempted to reduce the magnitude of error in the individual trace element ingestion estimates. Results from a previous study conducted by Calabrese et al. (1989) were used to quantify these errors based on the following criteria: (1) a lag period of 28 hours was assumed for the passage of tracers ingested in food to the feces (this value was applied to all subject-day estimates); (2) a daily soil ingestion rate was estimated for each tracer for each 24-hour day a fecal sample was obtained; (3) the median tracer-based soil ingestion rate for each subject-day was determined; and (4) negative errors due to missing fecal samples at the end of the study period were also determined. Also, upper- and lower-bound estimates were determined based on criteria formed using an assumption of the magnitude of the relative standard deviation presented in another study conducted by Stanek and Calabrese (1995a). Daily soil ingestion rates for tracers that fell beyond the upper and lower ranges were excluded from subsequent calculations, and the median soil ingestion rates of the remaining tracer elements were considered the best estimate for that particular day. The magnitude of positive or negative error for a specific tracer per day was derived by determining the difference between the value for the tracer and the median value.

Table 5-13 presents the estimated magnitude of positive and negative error for six tracer elements in the children's study [conducted by Calabrese et al. (1989)]. The original non-negative mean soil ingestion rates (see Table 5-3) ranged from a low of 21 mg/day based on zirconium to a high of 459 mg/day based on vanadium. The adjusted mean soil ingestion rate after correcting for negative and positive errors ranged from 97 mg/day based on yttrium to 208 mg/day based on titanium. Calabrese and Stanek (1995) concluded that correcting for errors at the individual level for each tracer element provides more reliable estimates of soil ingestion.

5.3.3.3. *Stanek and Calabrese (1995b)—Soil Ingestion Estimates for Use in Site Evaluations Based on the Best Tracer Method*

Stanek and Calabrese (1995b) recalculated soil ingestion rates for adults and children from two previous studies, using data for eight tracers from Calabrese et al. (1989) and three tracers from Davis et al. (1990). Recalculations were performed using the BTM. This method selected the “best” tracer(s), by dividing the total amount of tracer in a particular child’s duplicate food sample by tracer concentration in that child’s soil sample to yield a food/soil (F/S) ratio. The F/S ratio was small when the tracer concentration in food was low compared to the tracer concentration in soil. Small F/S ratios were desirable because they lessened the impact of transit time error (the error that occurs when fecal output does not reflect food ingestion, due to fluctuation in gastrointestinal transit time) in the soil ingestion calculation.

For adults, Stanek and Calabrese (1995b) used data for eight tracers from the Calabrese et al. (1989) study to estimate soil ingestion by the BTM. The lowest F/S ratios were Zr and Al and the element with the highest F/S ratio was Mn. For soil ingestion estimates based on the median of the lowest four F/S ratios, the tracers contributing most often to the soil ingestion estimates were Al, Si, Ti, Y, V, and Zr. Using the median of the soil ingestion rates based on the best four tracer elements, the average adult soil ingestion rate was estimated to be 64 mg/day with a median of 87 mg/day. The 95th percentile soil ingestion estimate was 142 mg/day. These estimates are based on 18 subject weeks for the six adult volunteers described in Calabrese et al. (1989).

The BTM used a ranking scheme of F/S ratios to determine the best tracers for use in the ingestion rate calculation. To reduce the impact of biases that may occur as a result of sources of fecal tracers other than food or soil, the median of soil ingestion estimates based on the four lowest F/S ratios was used to represent soil ingestion.

Using the lowest four F/S ratios for each individual, calculated on a per-week ("subject-week") basis, the median of the soil ingestion estimates from the Calabrese et al. (1989) study most often included aluminum, silicon, titanium, yttrium, and zirconium. Based on the median of soil ingestion estimates from the best four tracers, the mean soil ingestion rate for children was 132 mg/day and the median was 33 mg/day. The 95th percentile value was 154 mg/day. For the 101 children in the Davis et al. (1990) study, the mean soil ingestion rate was 69 mg/day and the median soil ingestion rate was 44 mg/day. The 95th percentile estimate was 246 mg/day. These data are based on the three tracers (i.e., aluminum, silicon, and titanium) from the Davis et al. (1990) study. When the results for the 128 subject-weeks in Calabrese et al. (1989) and 101 children in Davis et al. (1990) were combined, soil ingestion for children was estimated to be 104 mg/day (mean); 37 mg/day (median); and 217 mg/day (95th percentile), using the BTM.

5.3.3.4. *Hogan et al. (1998)—Integrated Exposure Uptake Biokinetic Model for Lead in Children: Empirical Comparisons With Epidemiologic Data*

Hogan et al. (1998) used the biokinetic model comparison methodology to review the measured blood lead levels of 478 children. These children were a subset of the entire population of children living in three historic lead smelting communities (Palmerton, Pennsylvania; Madison County, Illinois; and southeastern Kansas/southwestern Missouri), whose environmental lead exposures (soil and dust lead levels) had been studied as part of public health evaluations in these communities. The study populations were, in general, random samples of children 6 months to 7 years of age. Children who had lived in their residence for less than 3 months or those reported by their parents to be away from home more than 10 hours per week (>20 hours/week for the Pennsylvania data set) were excluded due to lack of information regarding lead exposure at the secondary location. The nature of the soil and dust exposures for the residential study population were typical, with the sample size considered sufficiently large to ensure that a wide enough range of children's behavior would be spanned by the data. Comparisons were made for a number of exposure factors, including age, location, time spent away from home, time spent outside, and whether or not children took food outside to eat.

The IEUBK model is a biokinetic model for predicting children's blood lead levels that uses measurements of lead content in house dust, soil, drinking water, food, and air, and child-specific estimates of intake for each exposure medium (dust, soil, drinking water, food and air). Model users can also use default assumptions for the lead contents and intake rates for each exposure medium when they do not have specific information for each child.

Hogan et al. (1998) compared children's measured blood lead levels with biokinetic model predictions (IEUBK version 0.99d) of blood lead levels, using the children's measured drinking water, soil, and dust lead contamination levels together with default IEUBK model inputs for soil and dust ingestion, relative proportions of soil and dust ingestion, lead bioavailability from soil and dust, and other model parameters. Thus, the default soil and dust ingestion rates in the model, and other default assumptions in the model, were tested by comparing measured blood lead levels with the model's predictions for those children's blood lead levels. Most IEUBK model kinetic and intake parameters were drawn independently from published literature (White et al., 1998; U.S. EPA, 1994b). Elimination parameters in particular had relatively less literature to draw upon (few data in children) and were fixed through a calibration exercise using a data set with children's blood lead levels paired with measured environmental lead exposures in and around their homes, while holding the other model parameters constant.

For Palmerton, Pennsylvania ($N = 34$), the community-wide geometric mean measured blood lead levels (6.8 µg/dL) were slightly over-predicted by the model (7.5 µg/dL); for southeastern Kansas/southwestern Missouri ($N = 111$), the blood lead levels (5.2 µg/dL) were slightly under-predicted (4.6 µg/dL), and for Madison County, Illinois ($N = 333$), the geometric mean measured blood lead levels matched the model predictions (5.9 µg/dL measured and predicted), with very slight differences in the 95% confidence interval. Although there may be uncertainty in these estimates, these results suggest that the default soil and dust ingestion rates used in this version of the IEUBK model (approximately 50 mg/day soil and 60 mg/day dust for a total soil + dust ingestion of 110 mg/day, averaged over children ages 1 through 6) may be roughly accurate in representing the central tendency soil and dust ingestion rates of residence-dwelling children in the three locations studied.

5.3.3.5. *Özkaynak et al. (2011)—Modeled Estimates of Soil and Dust Ingestion Rates for Children*

Özkaynak et al. (2011) developed soil and dust ingestion rates for children 3 to <6 years of age using U.S. EPA's SHEDS model for multimedia pollutants (SHEDS-Multimedia). The authors had two main objectives for this research: (1) to demonstrate an application of the SHEDS model while identifying and quantifying the key factors contributing to the predicted variability and uncertainty in the soil and dust ingestion exposure estimates, and (2) to compare the modeled results to existing tracer-element field measurements. The SHEDS model is a physically based probabilistic exposure model, which combines diary information on sequential time spent in different locations and activities drawn from U.S. EPA's Consolidated Human Activity Database (CHAD), with micro-activity data (e.g., hand-to-mouth frequency, hand-to-surface frequency), surface/object soil or dust loadings, and other exposure factors (e.g., soil-to-skin adherence, saliva removal efficiency). The SHEDS model generates simulated individuals, who are then followed through time, generally up to one year. The model computes changes to their exposure at the diary event level.

For this study, an indirect modeling approach was used, in which soil and dust were assumed to first adhere to the hands, and remain until washed off or ingested by mouthing. The object-to-mouth pathway for soil/dust ingestion was also addressed. For this application of the SHEDS model, however, other avenues of soil/dust ingestion were not considered. Outdoor matter was designated as "soil" and indoor matter as "dust." Estimates for the distributions of exposure factors such as activity, time outdoors, environmental concentrations, soil-skin and dust-skin transfer, hand washing frequency and efficiency, hand-mouthing frequency, area of object or hand mouthed, mouthing removal rates, and other variables were obtained from the literature. These input variables were used in this SHEDS model application to generate estimates of soil and dust ingestion rates for a simulated population of 1,000. Both sensitivity and uncertainty analyses were conducted. Based on the sensitivity analysis, the model results are the most sensitive to dust loadings on carpet and hard floor surfaces; soil-skin adherence factor; hand mouthing frequency, and; mean number of hand washes per day. Based on 200 uncertainty simulations that were conducted, the modeling uncertainties were seen to be asymmetrically distributed around the 50^{th} (median) or the central variability distribution.

Table 5-14 shows the predicted soil- and dust-ingestion rates. Mean total soil and dust ingestion was predicted to be 68 mg/day, with approximately 60% originating from soil ingestion, 30% from dust on hands, and 10% from dust on objects. Hand-to-mouth soil and dust ingestion was found to be the most important pathway, followed by hand-to-mouth dust ingestion, then object-to-mouth dust ingestion. The authors noted that these modeled estimates were found to be consistent with other soil/dust ingestion values in the literature, but slightly lower than the central tendency value of 100 mg/day recommended in U.S. EPA's *Child-Specific Exposure Factors Handbook* (U.S. EPA, 2008).

The advantages of this study include the fact that the SHEDS methodology can be applied to specific study populations of interest, a wide range of input parameters can be applied, and a full range of distributions can be generated. The primary limitation of this study is the lack of data for some of the input variables. Data needs include additional information on the activities and environments of children in younger age groups, including children with high hand-to-mouth, object-to-mouth, and pica behaviors, and information on skin adherence and dust loadings on indoor objects and floors. In addition, other age groups of interest were not included because of lack of data for some of the input variables.

5.3.4. Relevant Studies of Primary Analysis

The following studies are classified as relevant rather than key. The tracer element studies described in this section are not designated as key because the methodology to account for non-soil tracer exposures was not as well-developed as the methodology in the U.S. tracer element studies described in Sections 5.3.2 and 5.3.3, or because they do not provide a quantitative estimate of soil ingestion. However, the method of Clausing et al. (1987) was used in developing biokinetic model default soil and dust ingestion rates (U.S. EPA, 1994a) used in the Hogan et al. (1998) study, which was designated as key. In the survey response studies, in most cases the studies were of a non-randomized design, insufficient information was provided to determine important details regarding study design, or no data were provided to allow quantitative estimates of soil and/or dust ingestion rates.

5.3.4.1. *Dickins and Ford (1942)—Geophagy (Dirt Eating) Among Mississippi Negro School Children*

Dickens and Ford conducted a survey response study of rural Black school children (4th grade and above) in Oktibbeha County, Mississippi in September 1941. A total of 52 of 207 children (18 of 69 boys and 34 of 138 girls) studied gave positive responses to questions administered in a test-taking format regarding having eaten dirt in the previous 10 to 16 days. The authors stated that the study sample likely was more representative of the higher socioeconomic levels in the community, because older children from lower socioeconomic levels sometimes left school in order to work, and because children in the lower grades, who were more socioeconomically representative of the overall community, were excluded from the study. Clay was identified as the predominant type of soil eaten.

5.3.4.2. *Ferguson and Keaton (1950)—Studies of the Diets of Pregnant Women in Mississippi: II Diet Patterns*

Ferguson and Keaton (1950) conducted a survey response study of a group of 361 pregnant women receiving health care at the Mississippi State Board of Health, who were interviewed regarding their diet, including the consumption of clay or starch. All of the women were from the lowest economic and educational level in the area, and 92% were Black. Of the Black women, 27% reported clay-eating and 41% starch-eating. In the group of White women, 7 and 10% reporting clay- and starch-eating, respectively. The amount of starch eaten ranged from 2−3 small lumps to 3 boxes (24 ounces) per day. The amount of clay eaten ranged from one tablespoon to one cup per day.

5.3.4.3. *Cooper (1957)—Pica: A Survey of the Historical Literature as Well as Reports From the Fields of Veterinary Medicine and Anthropology, the Present Study of Pica in Young Children, and a Discussion of Its Pediatric and Psychological Implications*

Cooper (1957) conducted a non-randomized survey response study in the 1950s of children age 7 months or older referred to a Baltimore, Maryland mental hygiene clinic. For 86 out of 784 children studied, parents or caretakers gave positive responses to the question, “Does your child have a habit, or did he ever have a habit, of eating dirt, plaster, ashes, etc.?” and identified dirt, or dirt combined with other substances, as the substance ingested. Cooper (1957) described a pattern of pica behavior, including ingesting substances other than soil, being most common between ages 2 and 4 or 5 years, with one of the 86 children ingesting clay at age 10 years and 9 months.

5.3.4.4. *Barltrop (1966)—The Prevalence of Pica*

Barltrop (1966) conducted a randomized survey response study of children born in Boston, Massachusetts between 1958 and 1962, inclusive, whose parents resided in Boston and who were neither illegitimate nor adopted. A stratified random subsample of 500 of these children was contacted for in-person caregiver interviews, in which a total of 186 families (37%) participated. A separate stratified subsample of 1,000 children was selected for a mailed survey, in which 277 (28%) of the families participated. Interview-obtained data regarding care-giver reports of pica (in this study is defined as placing non-food items in the mouth and swallowing them) behavior in all children ages 1 to 6 years in the 186 families (N = 439) indicated 19 had ingested dirt (defined as yard dirt, house dust, plant-pot soil, pebbles, ashes, cigarette ash, glass fragments, lint, and hair combings) in the preceding 14 days. It does not appear that these data were corrected for unequal selection probability in the stratified random sample, nor were they corrected for non-response bias. Interviews were conducted in the March/April time frame, presumably in 1964. Mail-survey obtained data regarding caregiver reports of pica in the preceding 14 days indicated that 39 of 277 children had ingested dirt, presumably using the same definition as above. Barltrop (1966) mentions several possible limitations of the study, including non-participation bias and respondents’ memory, or recall, effects.

5.3.4.5. *Bruhn and Pangborn (1971)—Reported Incidence of Pica Among Migrant Families*

Bruhn and Pangborn (1971) conducted a survey among 91 low income families of migrant agricultural workers in California in May through August 1969. Families were of Mexican descent in two labor camps (Madison camp, 10 miles west of Woodland, and Davis camp, 10 miles east of Davis) and were “Anglo” families at the Harney Lane camp 17 miles north of Stockton. Participation was 34 of 50 families at the Madison camp, 31 of 50 families at the Davis camp, and 26 of 26 families at the Harney Lane camp. Respondents for the studied families (primarily wives) gave positive responses to open-ended questions such as "Do you know of anyone who eats dirt or laundry starch?" Bruhn and Pangborn (1971) apparently asked a modified version of this question pertaining to the respondents' own or relatives' families. They reported 18% (12 of 65) of Mexican families' respondents as giving positive responses for consumption of "dirt" among children within the Mexican respondents' own or relatives' families. They reported 42% (11 of 26) of "Anglo" families' respondents as giving positive responses for consumption of "dirt" among children within the Anglo respondents' own or relatives' families.

5.3.4.6. *Robischon (1971)—Pica Practice and Other Hand-Mouth Behavior and Children's Developmental Level*

A survey response sample of 19- to 24-month old children examined at an urban well-child clinic in the late 1960s or 1970 in an unspecified location indicated that 48 of the 130 children whose caregivers were interviewed, exhibited pica behavior (defined as "ate non-edibles more than once a week"). The specific substances eaten were reported for 30 of the 48 children. All except 2 of the 30 children habitually ate more than one non-edible substance. The soil and dust-like substances reported as eaten by these 30 children were: ashes (17), "earth" (5), dust (3), fuzz from rugs (2), clay (1), and pebbles/stones (1). Caregivers for some of the study subjects (between 0 and 52 of the 130 subjects, exact number not specified) reported that the children "ate non-edibles less than once a week."

5.3.4.7. *Bronstein and Dollar (1974)—Pica in Pregnancy*

The frequency and effects of pica behavior was investigated by Bronstein and Dollar (1974) in 410 pregnant, low-income women from both urban (N = 201) and rural (N = 209) areas in Georgia. The women selected were part of the Nutrition Demonstration Project, a study investigating the effect of nutrition on the outcome of the pregnancy, conducted at the Eugene Talmadge Memorial Hospital and University Hospital in Augusta, Georgia. During their initial prenatal visit, each patient was interviewed by a nutrition counselor who questioned her food frequency, social and dietary history, and the presence of pica. Patients were categorized by age, parity, and place of residence (rural or urban).

Of the 410 women interviewed, 65 (16%) stated that they practiced pica. A variety of substances were ingested, with laundry starch being the most common. There was no significant difference in the practice of pica between rural and urban women, although older rural women (20−35 years) showed a greater tendency to practice pica than younger rural or urban women (<20 years). The number of previous pregnancies did not influence the practice of pica. The authors noted that the frequency of pica among rural patients had declined from a previous study conducted 8 years earlier, and attributed the reduction to a program of intensified nutrition education and counseling provided in the area. No specific information on the amount of pica substances ingested was provided by this study, and the data are more than 30 years old.

5.3.4.8. *Hook (1978)—Dietary Cravings and Aversions During Pregnancy*

Hook (1978) conducted interviews of 250 women who had each delivered a live infant at two New York hospitals; the interviews took place in 1975. The mothers were first asked about any differences in consumption of seven beverages during their pregnancy, and the reasons for any changes. They were then asked, without mentioning specific items, about any cravings or aversions for other foods or non-food items that may have developed at any time during their pregnancy.

Non-food items reportedly ingested during pregnancy were ice, reported by three women, and chalk from a river clay bank, reported by one woman. In addition, one woman reported an aversion to non-food items (specific non-food item not reported). No quantity data were provided by this study.

5.3.4.9. *Binder et al. (1986)—Estimating Soil Ingestion: The Use of Tracer Elements in Estimating the Amount of Soil Ingested by Young Children*

Binder et al. (1986) used a tracer technique modified from a method previously used to measure soil ingestion among grazing animals to study the ingestion of soil among children 1 to 3 years of age who wore diapers. The children were studied during the summer of 1984 as part of a larger study of residents living near a lead smelter in East Helena, Montana. Soiled diapers were collected over a 3-day period from 65 children (42 males and 23 females), and composited samples of soil were obtained from the children's yards. Both excreta and soil samples were analyzed for aluminum, silicon, and titanium. These elements were found in soil but were thought to be poorly absorbed in the gut and to have been present in the diet only in limited quantities. Excreta measurements were obtained for 59 of the children.

Soil ingestion by each child was estimated on the basis of each of the three tracer elements using a standard assumed fecal dry weight of 15 g/day, and the following equation (5-2):

$$T_{i,e} = \frac{f_{i,e} \times F_i}{S_{i,e}} \qquad \text{(Eqn. 5-2)}$$

where:

$T_{i,e}$ = estimated soil ingestion for child i based on element e (g/day),
$f_{i,e}$ = concentration of element e in fecal sample of child i (mg/g),
F_i = fecal dry weight (g/day), and
$S_{i,e}$ = concentration of element e in child i's yard soil (mg/g).

The analysis assumed that (1) the tracer elements were neither lost nor introduced during sample processing; (2) the soil ingested by children originates primarily from their own yards; and (3) that absorption of the tracer elements by children occurred in only small amounts. The study did not distinguish between ingestion of soil and house dust, nor did it account for the presence of the tracer elements in ingested foods or medicines.

The arithmetic mean quantity of soil ingested by the children in the Binder et al. (1986) study was estimated to be 181 mg/day (range 25 to 1,324) based on the aluminum tracer; 184 mg/day (range 31 to 799) based on the silicon tracer; and 1,834 mg/day (range 4 to 17,076) based on the titanium tracer (see Table 5-15). The overall mean soil ingestion estimate, based on the minimum of the three individual tracer estimates for each child, was 108 mg/day (range 4 to 708). The median values were 121 mg/day, 136 mg/day, and 618 mg/day for aluminum, silicon, and titanium, respectively. The 95th percentile values for aluminum, silicon, and titanium were 584 mg/day, 578 mg/day, and 9,590 mg/day, respectively. The 95th percentile value based on the minimum of the three individual tracer estimates for each child was 386 mg/day.

The authors were not able to explain the difference between the results for titanium and for the other two elements, but they speculated that unrecognized sources of titanium in the diet or in the laboratory processing of stool samples may have accounted for the increased levels. The frequency distribution graph of soil ingestion estimates based on titanium shows that a group of 21 children had particularly high titanium values (i.e., >1,000 mg/day). The remainder of the children showed titanium ingestion estimates at lower levels, with a distribution more comparable to that of the other elements.

5.3.4.10. *Clausing et al. (1987)—A Method for Estimating Soil Ingestion by Children*

Clausing et al. (1987) conducted a soil ingestion study with Dutch children using a tracer element methodology. Clausing et al. (1987) measured aluminum, titanium, and acid-insoluble residue contents of fecal samples from children aged 2 to 4 years attending a nursery school, and for samples of playground dirt at that school. Over a 5-day period, 27 daily fecal samples were obtained for 18 children. Using the average soil concentrations present at the school, and assuming a standard fecal dry weight of 10 g/day, soil ingestion was estimated for each tracer. Six hospitalized, bedridden children served as a control group, representing children who had very limited access to soil; eight daily fecal samples were collected from the hospitalized children.

Without correcting for the tracer element contribution from background sources, represented by the hospitalized children's soil ingestion estimates, the aluminum-based soil ingestion estimates for the school children in this study ranged from 23 to 979 mg/day, the AIR-based estimates ranged from 48 to 362 mg/day, and the titanium-based estimates ranged from 64 to 11,620 mg/day. As in the Binder et al. (1986) study, a fraction of the children (6/18) showed titanium values above 1,000 mg/day, with most of the remaining children showing substantially lower values. Calculating an arithmetic mean quantity of soil ingested based on each fecal sample yielded 230 mg/day for aluminum; 129 mg/day for AIR, and 1,430 mg/day for titanium (see Table 5-16). Based on the LTM and averaging across each fecal sample, the arithmetic mean soil ingestion was estimated to be 105 mg/day with a population standard deviation of 67 mg/day (range 23 to 362 mg/day); geometric mean soil ingestion was estimated to be 90 mg/day. Use of the LTM assumed that "the maximum amount of soil ingested corresponded with the lowest estimate from the three tracers" (Clausing et al., 1987).

The hospitalized children's arithmetic mean aluminum-based soil ingestion estimate was 56 mg/day; titanium-based estimates included estimates for three of the six children that exceeded 1,000 mg/day, with the remaining three children in the range of 28 to 58 mg/day (see Table 5-17). AIR measurements were not reported for the hospitalized children. Using the LTM method, the mean soil ingestion rate was estimated to be 49 mg/day with a population standard deviation of 22 mg/day (range 26 to 84 mg/day). The geometric mean soil ingestion rate was 45 mg/day. The hospitalized children's data suggested a major non-soil source of titanium for some children and a background non-soil source of aluminum. However, conditions specific to hospitalization (e.g., medications) were not considered.

Clausing et al. (1987) estimated that the average soil ingestion of the nursery school children was 56 mg/day, after subtracting the mean LTM soil ingestion for the hospitalized children (49 mg/day) from the nursery school children's mean LTM soil ingestion (105 mg/day), to account for background tracer intake from dietary and other non-soil sources.

5.3.4.11. *Calabrese et al. (1990)—Preliminary Adult Soil Ingestion Estimates: Results of a Pilot Study*

Calabrese et al. (1990) studied six adults to evaluate the extent to which they ingest soil. This adult study was originally part of the children soil ingestion study (Calabrese et al., 1989) and was used to validate part of the analytical methodology used in the children's study. The participants were six healthy adults, three males and three females, 25−41 years old. Each volunteer ingested one empty gelatin capsule at breakfast and one at dinner Monday, Tuesday, and Wednesday during the first week of the study. During the second week, they ingested 50 milligrams of sterilized soil within a gelatin capsule at breakfast and at dinner (a total of 100 milligrams of sterilized soil per day) for 3 days. For the third week, the participants ingested 250 milligrams of sterilized soil in a gelatin capsule at breakfast and at dinner (a total of 500 milligrams of soil per day) during the 3 days. Duplicate meal samples (food and beverage) were collected from the six adults. The sample included all foods ingested from breakfast Monday, through the evening meal Wednesday during each of the 3 weeks. In addition, all medications and vitamins ingested by the adults were collected. Total excretory output was collected from Monday noon through Friday midnight over 3 consecutive weeks.

Data obtained from the first week, when empty gelatin capsules were ingested, were used to estimate soil intake by adults. On the basis of recovery values, Al, Si, Y, and Zr were considered the most valid tracers. The mean values for these four tracers were: Al, 110 milligrams; Si, 30 milligrams; Y, 63 milligrams; and Zr, 134 mg. A limitation of this study is the small sample size.

5.3.4.12. *Cooksey (1995)—Pica and Olfactory Craving of Pregnancy: How Deep Are the Secrets?*

Postpartum interviews were conducted between 1992 and 1994 of 300 women at a mid-western hospital, to document their experiences of pica behavior. The majority of women were Black and low-income, and ranged in age from 13 to 42 years. In addition to questions regarding nutrition, each woman was asked if during her pregnancy she experienced a craving to eat ice or other things that are not food.

Of the 300 women, 194 (65%) described ingesting one or more pica substances during their pregnancy, and the majority (78%) ate ice/freezer frost alone or in addition to other pica substances. Reported quantities of items ingested on a daily basis were three to four 8-pound bags of ice, two to three boxes of cornstarch, two cans of baking powder, one cereal bowl of dirt, five quarts of freezer frost, and one large can of powdered cleanser.

5.3.4.13. *Smulian et al. (1995)—Pica in a Rural Obstetric Population*

In 1992, Smulian et al. (1995) conducted a survey response study of pica in a convenience sample of 125 pregnant women in Muscogee County, Georgia, who ranged in age from 12 to 37 years. Of these, 73 were Black, 47 were White, 4 were Hispanic, and 1 was Asian. Interviews were conducted at the time of the first prenatal visit, using non-directive questionnaires to obtain information regarding substances ingested as well as patterns of pica behavior and influences on pica behavior. Only women ingesting non-food items were considered to have pica. Ingestion of ice was included as a pica behavior only if the ice was reported to be ingested multiple times per day, if the ice was purchased solely for ingestion, or if the ice was obtained from an unusual source such as freezer frost.

The overall prevalence of pica behavior in this study was 14.4% (18 of 125 women), and was highest among Black women (17.8%). There was no significant difference between groups with respect to age, race, weight, or gestational age at the time of enrollment in the study. The most common form of pica was ice eating (pagophagia), reported by 44.4% of the patients. Nine of the women reported information on the frequency and amount of the substances they were ingesting. Of these women, 66.7% reported daily consumption and 33.3% reported pica behavior three times per week. Soap, paint chips, or burnt matches were reportedly ingested 3 days per week. One patient ate ice 60 times per week. Women who ate dirt or clay reported ingesting 0.5−1 pound per week. The largest amount of ice consumed was five pounds per day.

5.3.4.14. *Grigsby et al. (1999)—Chalk Eating in Middle Georgia: A Culture-Bound Syndrome of Pica?*

Grigsby et al. (1999) investigated the ingestion of kaolin, also known as white dirt, chalk, or white clay, in the central Georgia Piedmont area as a culture-bound syndrome. A total of 21 individuals who consumed kaolin at the time or had a history of consuming kaolin were interviewed, using a seven-item, one-page interview protocol. All of those interviewed were Black, ranging in age from 28 to 88 years (mean age of 46.5 years), and all were female except for one.

Reasons for eating kaolin included liking the taste, being pregnant, craving it, and to gain weight. Eight respondents indicated that they obtained the kaolin from others, five reported getting it directly from the earth, four purchased it from a store, and two obtained it from a kaolin pit mine. The majority of the respondents reported that they liked the taste and feel of the kaolin as they ate it. Only three individuals reported knowing either males or White persons who consumed kaolin. Most individuals were not forthcoming in discussing their ingestion of kaolin and recognized that their behavior was unusual.

The study suggests that kaolin-eating is primarily practiced by Black women who were introduced to the behavior by family members or friends, during childhood or pregnancy. The authors concluded that kaolin ingestion is a culturally-transmitted form of pica, not associated with any other psychopathology. Although information on kaolin eating habits and attitudes were provided by this study, no quantitative information on consumption was included, and the sample population was small and non-random.

5.3.4.15. *Ward and Kutner (1999)—Reported Pica Behavior in a Sample of Incident Dialysis Patients*

Structured interviews were conducted with a sample of 226 dialysis patients in the metropolitan Atlanta, Georgia area from September 1996 to September 1997. Interviewers were trained in nutrition data collection methods, and patients also received a 3-day diet diary that they were asked to complete and return by mail. If a subject reported a strong past or current food or non-food craving, a separate form was used to collect information to determine if this was a pica behavior.

Pica behavior was reported by 37 of the dialysis patients studied (16%), and most of these patients (31 of 37) reported that they were currently practicing some form of pica behavior. The patients' race and sex were significantly associated with pica behavior, with Black patients and women making up 86% and 84% of those reporting pica, respectively. Those reporting pica behavior were also younger than the remainder of the sample, and approximately 2 described a persistent craving for ice. Other pica items reportedly consumed included starch, dirt, flour, or aspirin.

5.3.4.16. *Simpson et al. (2000)—Pica During Pregnancy in Low-Income Women Born in Mexico*

Simpson et al. (2000) interviewed 225 Mexican-born women, aged 18−42 years (mean age of 25 years), using a questionnaire administered in Spanish. Subjects were recruited by approaching women in medical facilities that served low-income populations in the cities of Ensenada, Mexico ($N = 75$), and Santa Ana, Bakersfield, and East Los Angeles, California ($N = 150$). Criteria for participation were that the women had to be Mexican-born, speak Spanish as their primary language, and be pregnant or have been pregnant within the past year. Only data for U.S. women are included in this handbook.

Pica behavior was reported in 31% of the women interviewed in the United States. Table 5-18 shows the items ingested and the number of women reporting the pica behavior. Of the items ingested, only ice was said to be routinely eaten outside of pregnancy, and was only reported by U.S. women, probably because none of the low-income women interviewed in Mexico owned a refrigerator. Removing the 12 women who reported eating only ice from the survey lowers the percentage of U.S. women who reported pica behavior to 23%. Women said they engaged in pica behavior because of the taste, smell, or texture of the items, for medicinal purposes, or because of advice from someone, and one woman reported eating clay for religious reasons. Magnesium carbonate, a pica item not found to be previously reported in the literature, was reportedly consumed by 17% of women. The amount of magnesium carbonate ingested ranged from a quarter of a block to five blocks per day; the blocks were approximately the size of a 35-mm film box. No specific quantity information on the amounts of pica substances ingested was provided in the study.

5.3.4.17. *Obialo et al. (2001)—Clay Pica Has No Hematologic or Metabolic Correlate to Chronic Hemodialysis Patients*

A total of 138 dialysis patients at the Morehouse School of Medicine, Atlanta, Georgia, were interviewed about their unusual cravings or food habits. The patients were Black and ranged in age from 37 to 78 years.

Thirty of the patients (22%) reported some form of pica behavior, while 13 patients (9.4%) reported clay pica. The patients with clay pica reported daily consumption of 225−450 grams of clay.

5.3.4.18. *Klitzman et al. (2002)—Lead Poisoning Among Pregnant Women in New York City: Risk Factors and Screening Practices*

Klitzman et al. (2002) interviewed 33 pregnant women whose blood lead levels were >20 µg/dL as reported to the New York City Department of Health between 1996 and 1999. The median age of the women was 24 years (range of 15 to 43 years), and the majority were foreign born. The women were interviewed regarding their work, reproductive and lead exposure history. A home visit was also conducted and included a visual inspection and a colorimetric swab test; consumable items suspected to contain lead were sent to a laboratory for analysis.

There were 13 women (39%) who reported pica behavior during their current pregnancies. Of these, 10 reported eating soil, dirt or clay, 2 reported pulverizing and eating pottery, and 1 reported eating soap. One of the women reported eating approximately one quart of dirt daily from her backyard for the past three months. No other quantity data were reported.

5.3.5. Relevant Studies of Secondary Analysis

The secondary analysis literature on soil and dust ingestion rates gives important insights into methodological strengths and limitations. The tracer element studies described in this section are grouped to some extent according to methodological issues associated with the tracer element methodology. These methodological issues include attempting to determine the origins of apparent positive and negative bias in the methodologies, including: food input/fecal output misalignment; missed fecal samples; assumptions about children's fecal weights; particle sizes of, and relative contributions of soils and dusts to total soil and dust ingestion; and attempts to identify a "best" tracer element or combination of tracer elements. Potential error from using short-term studies' estimates for long term soil and dust ingestion behavior estimates is also discussed.

5.3.5.1. *Stanek and Calabrese (1995a)—Daily Estimates of Soil Ingestion in Children*

Stanek and Calabrese (1995a) presented a methodology that links the physical passage of food and fecal samples to construct daily soil ingestion estimates from daily food and fecal trace-element concentrations. Soil ingestion data for children obtained from the Amherst study (Calabrese et al., 1989) were reanalyzed by Stanek and Calabrese (1995a). A lag period of 28 hours between food intake and fecal output was assumed for all respondents. Day 1 for the food sample corresponded to the 24-hour period from midnight on Sunday to midnight on Monday of a study week; day 1 of the fecal sample corresponded to the 24-hour period from noon on Monday to noon on Tuesday. Based on these definitions, the food soil equivalent was subtracted from the fecal soil equivalent to obtain an estimate of soil ingestion for a trace element. A daily overall ingestion estimate was constructed for each child as the median of trace element values remaining after tracers falling outside of a defined range around the overall median were excluded.

Table 5-19 presents adjusted estimates, modified according to the input/output misalignment correction, of mean daily soil ingestion per child (mg/day) for the 64 study participants. The approach adopted in this paper led to changes in ingestion estimates from those presented in Calabrese et al. (1989).

Estimates of children's soil ingestion projected over a period of 365 days were derived by fitting lognormal distributions to the overall daily soil ingestion estimates using estimates modified according to the input/output misalignment correction (see Table 5-20). The estimated median value of the 64 respondents' daily soil ingestion averaged over a year was 75 mg/day, while the 95th percentile was 1,751 mg/day. In developing the 365-day soil ingestion estimates, data that were obtained over a short period of time (as is the case with all available soil ingestion studies) were extrapolated over a year. The 2-week study period may not reflect variability in tracer element ingestion over a year. While Stanek and Calabrese (1995a) attempted to address this through modeling of the long term ingestion, new uncertainties were introduced through the parametric modeling of the limited subject day data.

5.3.5.2. *Calabrese and Stanek (1992a)—What Proportion of Household Dust is Derived From Outdoor Soil?*

Calabrese and Stanek (1992a) estimated the amount of outdoor soil in indoor dust using statistical modeling. The model used soil and dust data from the 60 households that participated in the Calabrese et al. (1989) study, by preparing scatter plots of each tracer's concentration in soil versus dust. Correlation analysis of the scatter plots was performed. The scatter plots showed little evidence of a consistent relationship between outdoor soil and indoor dust concentrations. The model estimated the proportion of outdoor soil in indoor dust using the simplifying assumption that the following variables were constants in all houses: the amount of dust produced every day from both indoor and outdoor sources; the proportion of indoor dust due to outdoor soil; and the concentration of the tracer element in dust produced from indoor sources. Using these assumptions, the model predicted that 31.3% by weight of indoor dust came from outdoor soil. This model was then used to adjust the soil ingestion estimates from Calabrese et al. (1989).

5.3.5.3. *Calabrese et al. (1996)—Methodology to Estimate the Amount and Particle Size of Soil Ingested by Children: Implications for Exposure Assessment at Waste Sites*

Calabrese et al. (1996) examined the hypothesis that one cause of the variation between tracers seen in soil ingestion studies could be related to differences in soil tracer concentrations by particle size. This study, published prior to the Calabrese et al. (1997b) primary analysis study results, used laboratory analytical results for the Anaconda, Montana soil's tracer concentration after it had been sieved to a particle size of <250 µm in diameter [it was sieved to <2 mm soil particle size in Calabrese et al. (1997b)]. The smaller particle size was examined based on the assumption that children principally ingest soil of small particle size adhering to fingertips and under fingernails. For five of the tracers used in the original study (aluminum, silicon, titanium, yttrium, and zirconium), soil concentration was not changed by particle size. However, the soil concentrations of three tracers (lanthanum, cerium, and neodymium) were increased 2- to 4-fold at the smaller soil particle size. Soil ingestion estimates for these three tracers were decreased by approximately 60% at the 95th percentile compared to the Calabrese et al. (1997b) results.

5.3.5.4. *Stanek et al. (1999)—Soil Ingestion Estimates for Children in Anaconda Using Trace Element Concentrations in Different Particle Size Fractions*

Stanek et al. (1999) extended the findings from Calabrese et al. (1996) by quantifying trace element concentrations in soil based on sieving to particle sizes of 100−250 µm and to particle sizes of 53 to <100 µm. The earlier study (Calabrese et al., 1996) used particle sizes of 0−2 µm and 1−250 µm. This study used the data from soil concentrations from the Anaconda, Montana site reported by Calabrese et al. (1997b). Results of the study indicated that soil concentrations of aluminum, silicon, and titanium did not increase at the two finer particle size ranges measured. However, soil concentrations of cerium, lanthanum, and neodymium increased by a factor of 2.5 to 4.0 in the 100−250 µm particle size range when compared with the 0−2 µm particle size range. There was not a significant increase in concentration in the 53−100 µm particle size range.

5.3.5.5. *Stanek and Calabrese (2000)—Daily Soil Ingestion Estimates for Children at a Superfund Site*

Stanek and Calabrese (2000) reanalyzed the soil ingestion data from the Anaconda study. The authors assumed a lognormal distribution for the soil ingestion estimates in the Anaconda study to predict average soil ingestion for children over a longer time period. Using "best linear unbiased predictors," the authors predicted 95th percentile soil ingestion values over time periods of 7 days, 30 days, 90 days, and 365 days. The 95th percentile soil ingestion values were predicted to be 133 mg/day over 7 days, 112 mg/day over 30 days, 108 mg/day over 90 days, and 106 mg/day over 365 days. Based on this analysis, estimates of the distribution of longer term average soil ingestion are expected to be narrower, with the 95th percentile estimates being as much as 25% lower (Stanek and Calabrese, 2000).

5.3.5.6. *Stanek et al. (2001a)—Biasing Factors for Simple Soil Ingestion Estimates in Mass Balance Studies of Soil Ingestion*

In order to identify and evaluate biasing factors for soil ingestion estimates, the authors developed a simulation model based on data from previous soil ingestion studies. The soil ingestion data used in this model were taken from Calabrese et al. (1989) (the Amherst study); Davis et al. (1990) (southeastern Washington State); Calabrese et al. (1997b) (the Anaconda study); and Calabrese et al. (1997a) (soil-pica in Massachusetts), and relied only on the aluminum and silicon trace element estimates provided in these studies.

Of the biasing factors explored, the impact of study duration was the most striking, with a positive bias of more than 100% for 95th percentile estimates in a 4-day tracer element study. A smaller bias was observed for the impact of absorption of trace elements from food. Although the trace elements selected for use in these studies are believed to have low absorption, whatever amount is not accounted for will result in an underestimation of the soil ingestion distribution. In these simulations, the absorption of trace elements from food of up to 30% was shown to negatively bias the estimated soil ingestion distribution by less than 20 mg/day. No biasing effect was found for misidentifying play areas for soil sampling (i.e., ingested soil from a yard other than the subject's yard).

5.3.5.7. *Stanek et al. (2001b)—Soil Ingestion Distributions for Monte Carlo Risk Assessment in Children*

Stanek et al. (2001b) developed "best linear unbiased predictors" to reduce the biasing effect of short-term soil ingestion estimates. This study estimated the long-term average soil ingestion distribution using daily soil ingestion estimates from children who participated in the Anaconda, Montana study. In this long-term (annual) distribution, the soil ingestion estimates were: mean 31, median 24, 75th percentile 42, 90th percentile 75, and 95th percentile 91 mg/day.

5.3.5.8. *Von Lindern et al. (2003)—Assessing Remedial Effectiveness Through the Blood Lead: Soil/Dust Lead Relationship at the Bunker Hill Superfund Site in the Silver Valley of Idaho*

Similar to Hogan et al. (1998), von Lindern et al. (2003) used the IEUBK model to predict blood lead levels in a non-random sample of several hundred children ages 0−9 years in an area of northern Idaho from 1989−1998 during community-wide soil remediation. Von Lindern et al. (2003) used the IEUBK default soil and dust ingestion rates together with observed house dust/soil lead levels (and imputed values based on community soil and dust lead levels, when observations were missing). The authors compared the predicted blood lead levels with observed blood lead levels and found that the default IEUBK soil and dust ingestion rates and lead bioavailability value over-predicted blood lead levels, with the over-prediction decreasing as the community soil remediation progressed. The authors stated that the over-prediction may have been caused either by a default soil and dust ingestion that was too high, a default bioavailability value for lead that was too high, or some combination of the two. They also noted under-predictions for some children, for whom follow up interviews revealed exposures to lead sources not accounted for by the model, and noted that the study sample included many children with a short residence time within the community.

Von Lindern et al. (2003) developed a statistical model that apportioned the contributions of community soils, yard soils of the residence, and house dust to lead intake; the models' results suggested that community soils contributed more (50%) than neighborhood soils (28%) or yard soils (22%) to soil found in house dust of the studied children.

5.3.5.9. *Gavrelis et al. (2011)—An Analysis of the Proportion of the U.S. Population That Ingests Soil or Other Non-Food Substances*

Gavrelis et al. (2011) evaluated the prevalence of the U.S. population that ingests non-food substances such as soil, clay, starch, paint, or plaster. Data were compiled from the National Health and Nutrition Examination Survey (NHANES) collected from 1971−1975 (NHANES I) and 1976−1980 (NHANES II), which represent a complex, stratified, multistage, probability-cluster design and include nationwide probability samples of approximately 21,000 and 25,000 study participants, respectively. NHANES I surveyed people aged 1 to 74 years and NHANES II surveyed those 6 months to 74 years. The study population included women of childbearing age, people with low income status, the elderly, and preschool children, who represented an oversampling of specific groups in the population that were believed to have high risks for malnutrition. The survey questions were demographic, socioeconomic, dietary, and health-related queries, and included specific questions regarding soil and non-food substance ingestion. Survey questions for children under 12 years asked whether they consumed non-food substances including dirt or clay, starch, paint or plaster, and other materials (NHANES I) or about consumption of clay, starch, paint or plaster, dirt, and other materials (NHANES II). For participants over 12 years of age, the survey questions asked only about consumption of dirt or clay, starch, and other materials (NHANES I) or about non-food substances including clay, starch, and other materials (NHANES II). Age groupings used in this analysis vary slightly from the age group categories established by U.S. EPA and described in *Guidance on Selecting Age Groups for Monitoring and Assessing Childhood Exposures to Environmental Contaminants* (U.S. EPA, 2005). Other demographic parameters included sex (including pregnant and non-pregnant females); race (White, Black, and other); geography (urban and rural, with "urban" defined as populations ≥2,500); income level (ranging from $0−$9,999 up to >$20,000, or not stated); and highest grade head of household (population under 18 years) or respondent (population >18 years) attended. For statistical analysis, frequency estimates were generated for the proportion of the total U.S. population that reported consumption of dirt, clay, starch, paint or plaster, or other materials "considered unusual" using the appropriate NCHS sampling weights and responses to the relevant questions in NHANES I and II. NHANES I and II were evaluated separately, because the data sets did not provide components of the weight variable separately (i.e., probability of selection, non-response adjustment weight, and post-stratification weight).

Although the overall prevalence estimates were higher in NHANES I compared with NHANES II, similar patterns were generally observed across substance types and demographic groups studied. For NHANES I, the estimated prevalence of all non-food substance consumption in the United States for all ages combined was 2.5% (95% Confidence Interval [CI]: 2.2−2.9%), whereas for NHANES II, the estimated prevalence of all non-food substance consumption in the United States for all ages combined was 1.1% (95% CI: 1.0−1.2%). Table 5-21 provides the prevalence estimates by type of substance consumed for all ages combined. By type of substance, the estimated prevalence was greatest for dirt and clay consumption and lowest for starch. Figure 5-1, Figure 5-2, and Figure 5-3, respectively, show the prevalence of non-food substance consumption by age, race, and income. The most notable differences were seen across age, race (Black versus White), and income groups. For both NHANES I and II, prevalence for the ingestion of all non-food substances decreased with increasing age, was higher among Blacks (5.7%; 95% CI: 4.4−7.0%) as compared to Whites (2.1%; 95% CI: 1.8−2.5%), and was inversely related to income level, with prevalence of non-food consumption decreasing as household income increased. The estimated prevalence of all non-food substances for the 1 to <3 year age category was at least twice that of the next oldest category (3 to <6 years). Prevalence estimates were 22.7% (95% CI: 20.1–25.3%) for the 1 to <3 year age group based on NHANES I and 12% based on NHANES II. In contrast, prevalence estimates for the >21 year age group was 0.7% (95% CI: 0.5–1.0%) and 0.4% (95% CI: 0.3–0.5%) for NHANES I and NHANES II, respectively. Other differences related to geography (i.e., urban and rural), highest grade level of the household head, and sex were less remarkable. For NHANES I, for example, the estimated prevalence of non-food substance consumption was only slightly higher among females (2.9%; CI: 2.3−3.5%) compared to males (2.1%; CI: 1.8−2.5%) of all ages. For pregnant females, prevalence estimates (2.5%; 95% CI: 0.0−5.6%) for those 12 years and over were more than twice those for non-pregnant females (1.0%; 95% CI: 0.7−1.4%).

5.4. LIMITATIONS OF STUDY METHODOLOGIES

The three types of information needed to provide recommendations to exposure assessors on soil and dust ingestion rates among U.S. children include quantities of soil and dust ingested, frequency of high soil and dust ingestion episodes, and prevalence of high soil and dust ingesters. The methodologies provide different types of information: the tracer element, biokinetic model comparison, and activity pattern methodologies provide information on quantities of soil and dust ingested; the tracer element methodology provides limited evidence of the frequency of high soil ingestion episodes; the survey response methodology can shed light on prevalence of high soil ingesters and frequency of high soil ingestion episodes. The methodologies used to estimate soil and dust ingestion rates and prevalence of soil and dust ingestion behaviors have certain limitations, when used for the purpose of developing recommended soil and dust ingestion rates. These limitations may not have excluded specific studies from use in the development of recommended ingestion rates, but have been noted throughout this handbook. This section describes some of the known limitations, presents an evaluation of the current state of the science for U.S. children's soil and dust ingestion rates, and describes how the limitations affect the confidence ratings given to the recommendations.

5.4.1. Tracer Element Methodology

This section describes some previously identified limitations of the tracer element methodology as it has been implemented by U.S. researchers, as well as additional potential limitations that have not been explored. Some of these same limitations would also apply to the Dutch and Jamaican studies that used a control group of hospitalized children to account for dietary and pharmaceutical tracer intakes.

Binder et al. (1986) described some of the major and obvious limitations of the early U.S. tracer element methodology as follows:

> [T]he algorithm assumes that children ingest predominantly soil from their own yards and that concentrations of elements in composite soil samples from front and back yards are representative of overall concentrations in the yards....children probably eat a combination of soil and dust; the algorithm used does not distinguish between soil and dust ingestion....fecal sample weights...were much lower than expected...the assumption that aluminum, silicon and titanium are not absorbed is not entirely true....dietary intake of aluminum, silicon and titanium is not negligible when compared with the potential intake of these elements from soil....Before accepting these estimates as true values of soil ingestion in toddlers, we need a better understanding of the metabolisms of aluminum, silicon and titanium in children, and the validity of the assumptions we made in our calculations should be explored further.

The subsequent U.S. tracer element studies (Davis and Mirick, 2006; Calabrese et al., 1997b; Barnes, 1990; Davis et al., 1990; Calabrese et al., 1989) made some progress in addressing some of the Binder et al. (1986) study's stated limitations.

Regarding the issue of non-yard (community-wide) soil as a source of ingested soil, one study (Barnes, 1990; Calabrese et al., 1989) addressed this issue to some extent, by including samples of children's daycare center soil in the analysis. Calabrese et al. (1997b) attempted to address the issue by excluding children in daycare from the study sample frame. Homogeneity of community soils' tracer element content would play a role in whether this issue is an important biasing factor for the tracer element studies' estimates. Davis et al. (1990) evaluated community soils' aluminum, silicon, and titanium content and found little variation among 101 yards throughout the three-city area. Stanek et al. (2001a) concluded that there was "minimal impact" on estimates of soil ingestion due to mis-specifying a child's play area.

Regarding the issue of soil and dust both contributing to measured tracer element quantities in excreta samples, the key U.S. tracer element studies all attempted to address the issue by including samples of household dust in the analysis, and in some cases estimates are presented in the published articles that adjust soil ingestion estimates on the basis of the measured tracer elements found in the household dust. The relationship between soil ingestion rates and indoor settled dust ingestion rates has been evaluated in some of the secondary studies (Calabrese and Stanek, 1992a). An issue similar to the community-wide soil exposures in the previous paragraph could also exist with community-wide indoor dust exposures (such as dust found in schools and community buildings occupied by study subjects during or prior to the study period). A portion of the community-wide indoor dust exposures (due to occupying daycare facilities) was addressed in the Calabrese et al. (1989) and Barnes (1990) studies, but not in the other three key tracer element studies. In addition, if the key studies' vacuum cleaner collection method for household and daycare indoor settled dust samples influenced tracer element composition of indoor settled dust samples, the dust sample collection method would be another area of uncertainty with the key studies' indoor dust related estimates. The survey response studies suggest that some young children may prefer ingesting dust to ingesting soil. The existing literature on soil versus dust sources of children's lead exposure may provide useful information that has not yet been compiled for use in soil and dust ingestion recommendations.

Regarding the issue of fecal sample weights and the related issue of missing fecal and urine samples, the key tracer element studies have varying strengths and limitations. The Calabrese et al. (1989) article stated that wipes and toilet paper were not collected by the researchers, and thus underestimates of fecal quantities may have occurred. Calabrese et al. (1989) stated that cotton cloth diapers were supplied for use during the study; commodes apparently were used to collect both feces and urine for those children who were not using diapers. Barnes (1990) described cellulose and polyester disposable diapers with significant variability in silicon and titanium content and suggested that children's urine was not included in the analysis. Thus, it is unclear to what extent complete fecal and urine output was obtained, for each study subject. The Calabrese et al. (1997b) study did not describe missing fecal samples and did not state whether urinary tracer element quantities were used in the soil and dust ingestion estimates, but stated that wipes and toilet paper were not collected. Missing fecal samples may have resulted in negative bias in the estimates from both of these studies. Davis et al. (1990) and Davis and Mirick (2006) were limited to children who no longer wore diapers.

Missed fecal sample adjustments might affect those studies' estimates in either a positive or negative direction, due to the assumptions the authors made regarding the quantities of feces and urine in missed samples. Adjustments for missing fecal and urine samples could introduce errors sufficient to cause negative estimates if missed samples were heavier than the collected samples used in the soil and dust ingestion estimate calculations.

Regarding the issue of dietary intake, the key U.S. tracer element studies have all addressed dietary (and non-dietary, non-soil) intake by subtracting calculated estimates of these sources of tracer elements from excreta tracer element quantities, or by providing study subjects with personal hygiene products that were low in tracer element content. Applying the food and non-dietary, non-soil corrections required subtracting the tracer element contributions from these non-soil sources from the measured fecal/urine tracer element quantities. To perform this correction required assumptions to be made regarding the gastrointestinal transit time, or the time lag between inputs (food, non-dietary non-soil, and soil) and outputs (fecal and urine). The gastrointestinal transit time assumption introduced a new potential source of bias that some authors (Stanek and Calabrese, 1995a) called input/output misalignment or transit time error. Stanek and Calabrese (1995b) attempted to correct for this transit time error by using the BTM and focusing estimates on those tracers that had a low food/soil tracer concentration ratios. The lag time may also be a function of age. Davis et al. (1990) and Davis and Mirick (2006) assumed a 24-hour lag time in contrast to the 28-hour lag times used in Calabrese et al. (1989); Barnes (1990); and Calabrese et al. (1997b). ICRP (2003) suggested a lag time of 37 hours for one year old children and 5 to 15 year old children. Stanek and Calabrese (1995a) describe a method designed to reduce bias from this error source.

Regarding gastrointestinal absorption, the authors of three of the studies appeared to agree that the presence of silicon in urine represented evidence that silicon was being absorbed from the gastrointestinal tract (Davis and Mirick, 2006; Barnes, 1990; Davis et al., 1990; Calabrese et al., 1989). There was some evidence of aluminum absorption in Calabrese et al. (1989); Barnes (1990); Davis and Mirick (2006) stated that aluminum and titanium did not appear to have been absorbed, based on low urinary levels. Davis et al. (1990) stated that silicon appears to have been absorbed to a greater degree than aluminum and titanium, based on urine concentrations.

Aside from the gastrointestinal absorption, lag time, and missed fecal sample issues, Davis and Mirick (2006) offered another possible explanation for the negative soil and dust ingestion rates estimated for some study participants. Negative values result when the tracer amount in food and medicine is greater than that in urine/fecal matter. Given that some analytical error may occur, any overestimation of tracer amounts in the food samples would be greater than an overestimation in urine/feces, since the food samples were many times heavier than the urine and fecal samples.

Another limitation on accuracy of tracer element-based estimates of soil and dust ingestion relates to inaccuracies inherent in environmental sampling and laboratory analytical techniques. The "percent recovery" of different tracer elements varies [according to validation of the study methodology performed with adults who swallowed gelatin capsules with known quantities of sterilized soil, as part of the Calabrese et al. (1997b; 1989) studies]. Estimates based on a particular tracer element with a lower or higher recovery than the expected 100% in any of the study samples would be influenced in either a positive or negative direction, depending on the recoveries in the various samples and their degree of deviation from 100% (Calabrese et al., 1989). Soil/dust size fractions, and digestion/extraction methods of sample analysis may be additional limitations.

Davis et al. (1990) offered an assessment of the impact of swallowed toothpaste on the tracer-based estimates by adjusting estimates for those children whose caregivers reported that they had swallowed toothpaste. Davis et al. (1990) had supplied study children with toothpaste that had been pre-analyzed for its tracer element content, but it is not known to what extent the children actually used the supplied toothpaste. Similarly, Calabrese et al. (1997b; 1989) supplied children in the Amherst, Massachusetts and Anaconda, Montana studies with toothpaste containing low levels of most tracers, but it is unclear to what extent those children used the supplied toothpaste.

Other research suggests additional possible limitations that have not yet been explored. First, lymph tissue structures in the gastrointestinal tract might serve as reservoirs for titanium dioxide food additives and soil particles, which could bias estimates either upward or downward depending on tracers' entrapment within, or release from, these reservoirs during the study period (ICRP, 2003; Powell et al., 1996; Shepherd et al., 1987). Second, gastrointestinal uptake of silicon may have occurred, which could bias those estimates downward. Evidence of silicon's role in bone formation (Carlisle, 1980) supported by newer research on dietary silicon uptake (Jugdaohsingh et al., 2002); Van Dyck et al. (2000) suggests a possible negative bias in the silicon-based soil ingestion estimates, depending on the quantities of silicon absorbed by growing children. Third, regarding the potential for swallowed toothpaste to bias soil ingestion estimates upward, commercially available toothpaste may contain quantities of titanium and perhaps silicon and aluminum in the range that could be expected to affect the soil and dust ingestion estimates. Fourth, for those children who drank bottled or tap water during the study period, and did not include those drinking water samples in their duplicate food samples, slight upward bias may exist in some of the estimates for those children, since drinking water may contain small, but relevant, quantities of silicon and potentially other tracer elements. Fifth, the tracer element studies conducted to date have not explored the impact of soil properties' influence on toxicant uptake or excretion within the gastrointestinal tract. Nutrition researchers investigating influence of clay geophagy behavior on human nutrition have begun using in vitro models of the human digestion (Dominy et al., 2004; Hooda et al., 2004). A recent review (Wilson, 2003) covers a wide range of geophagy research in humans and various hypotheses proposed to explain soil ingestion behaviors, with emphasis on the soil properties of geophagy materials.

5.4.2. Biokinetic Model Comparison Methodology

It is possible that the IEUBK biokinetic model comparison methodology contained sources of both positive and negative bias, like the tracer element studies, and that the net impact of the competing biases was in either the positive or negative direction. U.S. EPA's judgment about the major sources of bias in biokinetic model comparison studies is that there may be several significant sources of bias. The first source of potential bias was the possibility that the biokinetic model failed to account for sources of lead exposure that are important for certain children. For these children, the model might either under-predict, or accurately predict, blood lead levels compared to actual measured lead levels. However, this result may actually mean that the default assumed lead intake rates via either soil and dust ingestion, or another lead source that is accounted for by the model, are too high. A second source of potential bias was use of the biokinetic model for predicting blood lead levels in children who have not spent a significant amount of time in the areas characterized as the main sources of environmental lead exposure. Modeling this population could result in either upward or downward biases in predicted blood lead levels. Comparing upward-biased predictions with actual measured blood lead levels and finding a relatively good match could lead to inferences that the model's default soil and dust ingestion rates are accurate, when in fact the children's soil and dust ingestion rates, or some other lead source, were actually higher than the default assumption. A third source of potential bias was the assumption within the model itself regarding the biokinetics of absorbed lead, which could result in either positively or negatively biased predictions and the same kinds of incorrect inferences as the second source of potential bias.

In addition, there was no extensive sensitivity analysis. The calibration step used to fix model parameters limits the degree that most parameters can reasonably be varied. Second, the IEUBK model was not designed to predict blood lead levels greater than 25−30 μg/dL; there are few data to develop such predictions and less to validate them. If there are site-specific data that indicate soil ingestion rates (or other ingestion/intake rates) are higher than the defaults on average (not for specific children), the site-specific data should be considered. U.S. EPA considers the default IEUBK value of 30% reasonable for most data sets/sites. Bioavailability has been assayed for soils similar to those in the calibration step and the empirical comparison data sets; 30% was used in the calibration step, and is therefore recommended for similar sites. The default provides a reasonable substitute when there are no specific data. Speciation of lead compounds for a particular exposure scenario could support adjusting bioavailability if they are known to differ strongly from 30%. In general, U.S. EPA supports using bioavailability rates determined for the particular soils of interest if available.

5.4.3. Activity Pattern Methodology

The limitations associated with the activity pattern methodology relate to the availability and quality of the underlying data used to model soil ingestion rates. Real-time hand recording, where observations are made by trained professionals (rather than parents), may offer the advantage of consistency in interpreting visible behaviors and may be less subjective than observations made by someone who maintains a care giving relationship to the child. On the other hand, young children's behavior may be influenced by the presence of unfamiliar people (Davis et al., 1995). Groot et al. (1998) indicated that parent observers perceived that deviating from their usual care giving behavior by observing and recording mouthing behavior appeared to have influenced the children's behavior. With video-transcription methodology, an assumption is made that the presence of the videographer or camera does not influence the child's behavior. This assumption may result in minimal biases introduced when filming newborns, or when the camera and videographer are not visible to the child. However, if the children being studied are older than newborns and can see the camera or videographer, biases may be introduced. Ferguson et al. (2006) described apprehension caused by videotaping and described situations where a child's awareness of the videotaping crew caused "play-acting" to occur, or parents indicated that the child was behaving differently during the taping session. Another possible source of measurement error may be introduced when children's movements or positions cause their mouthing not to be captured by the camera. Data transcription errors can bias results in either the negative or positive direction. Finally, measurement error can occur if situations arise in which care givers are absent during videotaping and researchers must stop videotaping and intervene to prevent risky behaviors (Zartarian et al., 1995). Survey response studies rely on responses to questions about a child's mouthing behavior posed to parents or care givers. Measurement errors from these studies could occur for a number of different reasons, including language/dialect differences between interviewers and respondents, question wording problems and lack of definitions for terms used in questions, differences in respondents' interpretation of questions, and recall/memory effects.

Other data collection methodologies (in-person interview, mailed questionnaire, or questions administered in "test" format in a school setting) may have had specific limitations. In-person interviews could result in either positive or negative response bias due to distractions posed by young children, especially when interview respondents simultaneously care for young children and answer questions. Other limitations include positive or negative response bias due to respondents' perceptions of a "correct" answer, question wording difficulties, lack of understanding of definitions of terms used, language and dialect differences between investigators and respondents, respondents' desires to avoid negative emotions associated with giving a particular type of answer, and respondent memory problems ("recall" effects) concerning past events. Mailed questionnaires have many of the same limitations as in-person interviews, but may allow respondents to respond when they are not distracted by childcare duties. An in-school test format is more problematic than either interviews or mailed surveys, because respondent bias related to teacher expectations could influence responses.

One approach to evaluating the degree of bias in survey response studies may be to make use of a surrogate biomarker indicator providing suggestive evidence of ingestion of significant quantities of soil (although quantitative estimates would not be possible). The biomarker technique measures the presence of serum antibodies to *Toxocara* species, a parasitic roundworm from cat and dog feces. Two U.S. studies have found associations between reported soil ingestion and positive serum antibody tests for *Toxocara* infection (Marmor et al., 1987; Glickman et al., 1981); a third (Nelson et al., 1996) has not, but the authors state that reliability of survey responses regarding soil ingestion may have been an issue. Further refinement of survey response methodologies, together with recent NHANES data on U.S. prevalence of positive serum antibody status regarding infection with *Toxocara* species, may be useful.

5.4.4. Key Studies: Representativeness of the U.S. Population

The two key studies of Dutch and Jamaican children may represent different conditions and different study populations than those in the United States; thus, it is unclear to what extent those children's soil ingestion behaviors may differ from U.S. children's soil ingestion behaviors. The subjects in the Davis and Mirick (2006) study may not have been representative of the general population since they were selected for their high compliance with the protocol from a previous study.

Limitations regarding the key studies performed in the United States for estimating soil and dust ingestion rates in the entire population of U.S. children ages 0 to <21 years fall into the broad categories of geographic range and demographics (age, sex, race/ethnicity, socioeconomic status).

Regarding geographic range, the two most obvious issues relate to soil types and climate. Soil properties might influence the soil ingestion estimates that are based on excreted tracer elements. The Davis et al. (1990); Calabrese et al. (1989); Barnes (1990); Davis and Mirick (2006); and Calabrese et al. (1997b) tracer element studies were in locations with soils that had sand content ranging from 21−80%, silt content ranging from 16−71%, and clay content ranging from 3−20% by weight, based on data from USDA (2008). The location of children in the Calabrese et al. (1997a) study was not specified, but due to the original survey response study's occurrence in western Massachusetts, the soil types in the vicinity of the Calabrese et al. (1997a) study are likely to be similar to those in the Calabrese et al. (1989) and Barnes (1990) study.

The Hogan et al. (1998) study included locations in the central part of the United States (an area along the Kansas/Missouri border, and an area in western Illinois) and one in the eastern United States (Palmerton, Pennsylvania). The only key study conducted in the southern part of the United States was Vermeer and Frate (1979).

Children might be outside and have access to soil in a very wide range of weather conditions (Wong et al., 2000). In the parts of the United States that experience moderate temperatures year-round, soil ingestion rates may be fairly evenly distributed throughout the year. During conditions of deep snow cover, extreme cold, or extreme heat, children could be expected to have minimal contact with outside soil. All children, regardless of location, could ingest soils located indoors in plant containers, soil derived particulates transported into dwellings as ambient airborne particulates, or outdoor soil tracked inside buildings by human or animal building occupants. Davis et al. (1990) did not find a clear or consistent association between the number of hours spent indoors per day and soil ingestion, but reported a consistent association between spending a greater number of hours outdoors and high (defined as the uppermost tertile) soil ingestion levels across all three tracers used.

The key tracer element studies all took place in northern latitudes. The temperature and precipitation patterns that occurred during these four studies' data collection periods were difficult to discern due to no mention of specific data collection dates in the published articles. The Calabrese et al. (1989) and Barnes (1990) study apparently took place in mid to late September 1987 in and near Amherst, Massachusetts; Calabrese et al. (1997b) apparently took place in late September and early October 1992, in Anaconda, Montana; Davis et al. (1990) took place in July, August, and September 1987, in Richland, Kennewick, and Pasco, Washington; and Davis and Mirick (2006) took place in the same Washington state location in late July, August, and very early September 1988 (raw data). Inferring exact data collection dates, a wide range of temperatures may have occurred during the four studies' data collection periods [daily lows from 22−60°F and 25−48°F, and daily highs from 53−81°F and 55−88°F in Calabrese et al. (1989) and Calabrese et al. (1997b), respectively, and daily lows from 51−72°F and 51−67°F, and daily highs from 69−103°F and 80−102°F in Davis et al. (1990) and Davis and Mirick (2006), respectively] (NCDC, 2008). Significant amounts of precipitation occurred during Calabrese et al. (1989) (more than 0.1 inches per 24-hour period) on several days; somewhat less precipitation was observed during Calabrese et al. (1997b); precipitation in Kennewick and Richland during the data collection periods of Davis et al. (1990) was almost non-existent; there was no recorded precipitation in Kennewick or Richland during the data collection period for Davis and Mirick (2006) (NCDC, 2008).

The key biokinetic model comparison study (Hogan et al., 1998) targeted three locations in more southerly latitudes (Pennsylvania, southern Illinois, and southern Kansas/Missouri) than the tracer element studies. The biokinetic model comparison methodology had an advantage over the tracer element studies in that the study represented long-term environmental exposures over periods up to several years that would include a range of seasons and climate conditions.

A brief review of the representativeness of the key studies' samples with respect to sex and age suggested that males and females were represented roughly equally in those studies for which study subjects' sex was stated. Children up to age 8 years were studied in seven of the nine studies, with an emphasis on younger children. Wong (1988); Calabrese and Stanek (1993); and Vermeer and Frate (1979) are the only studies with children 8 years or older.

A brief review of the representativeness of the key studies' samples with respect to socioeconomic status and racial/ethnic identity suggested that there were some discrepancies between the study subjects and the current U.S. population of children age 0 to <21 years. The single survey response study (Vermeer and Frate, 1979) was specifically targeted toward a predominantly rural Black population in a particular county in Mississippi. The tracer element studies are of predominantly White populations, apparently with limited representation from other racial and ethnic groups. The Amherst, Massachusetts study (Barnes, 1990; Calabrese et al., 1989) did not publish the study participants' socioeconomic status or racial and ethnic identities. The socioeconomic level of the Davis et al. (1990) studied children was reported to be primarily of middle to high income. Self-reported race and ethnicity of relatives of the children studied (in most cases, they were the parents of the children studied) in Davis et al. (1990) were White (86.5%), Asian (6.7%), Hispanic (4.8%), Native American (1.0%), and Other (1.0%), and the 91 married or living-as-married respondents identified their spouses as White (86.8%), Hispanic

(7.7%), Asian (4.4%), and Other (1.1%). Davis and Mirick (2006) did not state the race and ethnicity of the follow-up study participants, who were a subset of the original study participants from Davis et al. (1990). For the Calabrese et al. (1997b) study in Anaconda, Montana, population demographics were not presented in the published article. The study sample appeared to have been drawn from a door-to-door census of Anaconda residents that identified 642 toilet trained children who were less than 72 months of age. Of the 414 children participating in a companion study (out of the 642 eligible children identified), 271 had complete study data for that companion study, and of these 271, 97.4% were identified as White and the remaining 2.6% were identified as Native American, Black, Asian, and Hispanic (Hwang et al., 1997). The 64 children in the Calabrese et al. (1997b) study apparently were a stratified random sample (based on such factors as behavior during a previous study, the existence of a disability, or attendance in daycare) drawn from the 642 children identified in the door-to-door census. Presumably these children identified as similar races and ethnicities to the Hwang et al. (1997) study children. The Calabrese et al. (1997a) study indicated that 11 of the 12 children studied were White.

In summary, the geographic range of the key study populations was somewhat limited. Of those performed in the United States, locations included Massachusetts, Kansas, Montana, Missouri, Illinois, Washington, and Pennsylvania. The two most obvious issues regarding geographic range relate to soil types and climate. Soil types were not always described, so the representativeness of the key studies related to soil types and properties is unclear. The key tracer element studies all took place in northern latitudes. The only key study conducted in the southern part of the United States was Vermeer and Frate (1979).

In terms of sex and age, males and females were represented roughly equally in those studies for which study subjects' sex was stated, while the majority of children studied were under the age of eight. The tracer element studies are of predominantly White populations, with a single survey response study (Vermeer and Frate, 1979) targeted toward a rural Black population. Other racial and ethnic identities were not well reported among the key studies, nor was socioeconomic status. The socioeconomic level of the Davis et al. (1990) studied children was reported to be primarily of middle to high income.

5.5. SUMMARY OF SOIL AND DUST INGESTION ESTIMATES FROM KEY STUDIES

Table 5-22 summarizes the soil and dust ingestion estimates from the 12 key studies in chronological order. For the U.S. tracer element studies, in order to compare estimates that were calculated in a similar manner, the summary is limited to estimates that use the same basic algorithm of ([fecal and urine tracer content] - [food and medication tracer content])/[soil or dust tracer concentration]. Note that several of the published reanalyses suggest different variations on these algorithms, or suggest adjustments that should be made for various reasons (Calabrese and Stanek, 1995; Stanek and Calabrese, 1995b). Other reanalyses suggest that omitting some of the data according to statistical criteria would be a worthwhile exercise. Due to the current state of the science regarding soil and dust ingestion estimates, U.S. EPA does not advise omitting an individual's soil or dust ingestion estimate, based on statistical criteria, at this point in time.

There is a wide range of estimated soil and dust ingestion across key studies. Note that some of the soil-pica ingestion estimates from the tracer element studies were consistent with the estimated mean soil ingestion from the survey response study of geophagy behavior. The biokinetic model comparison methodology's confirmation of central tendency soil and dust ingestion default assumptions corresponded roughly with some of the central tendency tracer element study estimates. Also note that estimates based on the activity pattern methodology are comparable with estimates derived from the tracer element methodology.

5.6. DERIVATION OF RECOMMENDED SOIL AND DUST INGESTION VALUES

As stated earlier in this chapter, the key studies were used as the basis for developing the soil and dust ingestion recommendations shown in Table 5-1. The following sections describe in more detail how the recommended soil and dust ingestion values were derived.

5.6.1. Central Tendency Soil and Dust Ingestion Recommendations

For the central tendency recommendations shown in Table 5-1, Van Wijnen et al. (1990) published soil ingestion "LTM" estimates based on infants older than 6 weeks but less than 1 year old (exact ages unspecified). During "bad" weather (>4 days per week of precipitation), the geometric mean estimated LTM values were 67 and 94 milligrams soil (dry weight)/day; during “good” weather (<2 days/week of precipitation) the geometric mean estimated LTM values were 102 milligrams soil (dry weight)/day (van Wijnen et al., 1990). These values were not corrected to exclude dietary intake of the tracers on which they were based. The developers of the IEUBK model used these data as the basis for the default soil and dust intakes for the 6 to <12 month old infants in the IEUBK model (U.S. EPA, 1994b) of 38.25 milligrams soil/day and 46.75 mg house dust/day, for a total soil + dust intake default assumption of 85 mg/day for this age group (U.S. EPA, 1994a).

Further evidence of dust intake by infants has been conducted in the context of evaluating blood lead levels and the potential contributions of lead from three sources: bone turnover, food sources, and environmental exposures such as house dust. Manton et al. (2000) conducted a study with older infants and young children, and concluded that appreciable quantities of dust were ingested by infants. Gulson et al. (2001) studied younger infants than Manton et al. (2000) and did not explicitly include dust sources, but the authors acknowledged that, based on ratios of different isotopes of lead found in infants' blood and urine, there appeared to be a non-food, non-bone source of lead of environmental origin that contributed “minimally,” relative to food intakes and bone turnover in 0- to 6-month-old infants.

The Hogan et al. (1998) data for 38 infants (one group $N = 7$ and one group $N = 31$) indicated that the IEUBK default soil and dust estimate for 6 to <12 month olds (85 mg/day) over-predicted blood lead levels in this group, suggesting that applying an 85 mg soil + dust (38 mg soil + 47 mg house dust) per day estimate for 6 months' exposure may be too high for this life stage.

For the larger of two groups of infants aged 6 to <12 months in the Hogan et al. (1998) study ($N = 31$), the default IEUBK value of 85 mg/day predicted geometric mean blood lead levels of 5.2 µg/dL versus 3.8 µg/dL actual measured blood lead level (a ratio of 1.37). It is possible that the other major sources of lead accounted for in the IEUBK model (dietary and drinking water lead) are responsible for part of the over-prediction seen with the Hogan et al. (1998) study. Rounded to the ones place, the default assumed daily lead intakes were (dietary) 6 µg/day and (drinking water) 1 µg/day, compared to the soil lead intake of 8 µg/day and house dust lead intake of 9 µg/day (U.S. EPA, 1994b). The dietary lead intake default assumption thus might be expected to be responsible for the over-predictions as well as the soil and dust intake, since these three sources (diet, soil, and dust) comprise the majority of the total lead intake in the model. Data from Manton et al. (2000) suggest that the default assumption for dietary lead intake might be somewhat high (reported geometric mean daily lead intake from food in Manton et al. (2000) was 3.2 µg/day, arithmetic mean 3.3 µg/day).

Making use of the epidemiologic data from the larger group of 31 infants in the Hogan et al. (1998) study, it is possible to develop an extremely rough estimate of soil + dust intake by infants 6 weeks to <12 months of age. The ratio of the geometric mean IEUBK-predicted to actual measured blood lead levels in 31 infants was 1.37. This value may be used to adjust the soil and dust intake rate for the 6 to <12 month age range. Using the inverse of 1.37 (0.73) and multiplying the 85 mg/day soil + house dust intake rate by this value, gives an adjusted value of 62 mg/day soil + dust, rounded to one significant figure at 60 mg/day. The 38 mg soil/day intake rate, multiplied by the 0.73 adjustment factor, yields 28 mg soil per day (rounding to 30 mg soil per day); the 47 mg house dust/day intake rate multiplied by 0.73 yields 34 mg house dust per day (rounding to 30 mg house dust per day). These values, adjusted from the IEUBK default values, are the basis for the soil (30 mg/day) and dust (30 mg/day) recommendations for children aged 6 weeks to 12 months.

For children age 1 to <6 years, the IEUBK default values used in the Hogan et al. (1998) study were: 135 mg/day for 1, 2, and 3 year olds; 100 mg/day for 4 year olds; 90 mg/day for 5 year olds; and 85 mg/day for 6 year olds. These values were based on an assumption of 45% soil, 55% dust (U.S. EPA, 1994a). The time-averaged daily soil + dust ingestion rate for these 6 years of life is 113 mg/day, dry-weight basis. The Hogan et al. (1998) study found the following over- and under-predictions of blood lead levels, compared to actual measured blood lead levels, using the default values shown in Table 5-23. Apportioning the 113 mg/day, on average, into 45% soil and 55% dust (U.S. EPA, 1994a), yields an average for this age group of 51 mg/day soil, 62 mg/day dust. Rounded to one significant figure, these values are 50 and 60 mg/day, respectively. The 60 mg/day dust would be comprised of a combination of outdoor soil tracked indoors onto floors, indoor dust on floors, indoor settled dust on non-floor surfaces, and probably a certain amount of inhaled suspended dust that is swallowed and enters the gastrointestinal tract. Soil ingestion rates were assumed to be comparable for children age 1 to <6 years and 6 to <21 years, and therefore the same recommended values were used for both age groups. Estimates derived by Özkaynak et al. (2011) suggest soil and dust ingestion rates comparable to other estimates in the literature based on tracer element methodology (i.e., a mean value of 68 mg/day).

The recommended soil and dust ingestion rate of 50 mg/day for adults was taken from the overall mean value of 52 mg/day for the adults in the Davis and Mirick (2006) study. Based on this value, the recommended adult soil and dust ingestion value is estimated to be 50 mg/day. There are no available studies estimating the ingestion of dust by adults, therefore, the recommended values for soil and dust were derived from the soil + dust ingestion, assuming 45% soil and 55% dust contribution.

5.6.2. Upper Percentile, Soil Pica, and Geophagy Recommendations

Upper percentile estimates for children 3 to <6 years old were derived from Özkaynak et al. (2011) and Stanek and Calabrese (1995b). These two studies had similar estimates of 95th percentile value (i.e., 224 mg/day and 207 mg/day, respectively). Rounding to one significant figure, the recommended upper percentile estimate of soil and dust ingestion is 200 mg/day. Soil and dust ingestion recommendations were obtained from Özkaynak et al. (2011). For the upper percentile soil pica and geophagy recommendations shown in Table 5-1, two primary lines of evidence suggest that at least some U.S. children exhibit soil-pica behavior at least once during childhood. First, the survey response studies of reported soil ingestion behavior that were conducted in numerous U.S. locations and of different populations consistently yield a certain proportion of respondents who acknowledge soil ingestion by children. The surveys typically did not ask explicit and detailed questions about the soil ingestion incidents reported by the care givers who acknowledged soil ingestion in children. Responses conceivably could fall into three categories: (1) responses in which care givers interpret visible dirt on children's hands, and subsequent hand-to-mouth behavior, as soil ingestion; (2) responses in which care givers interpret intentional ingestion of clay, "dirt" or soil as soil ingestion; and (3) responses in which care givers regard observations of hand-to-mouth behavior of visible quantities of soil as soil ingestion. Knowledge of soils' bulk density allows inferences to be made that these latter observed hand-to-mouth soil ingestion incidents are likely to represent a quantity of soil that meets the quantity part of the definition of soil-pica used in this chapter, or 1,000 mg. Occasionally, what is not known from survey response studies is whether the latter type of survey responses include responses regarding repeated soil ingestion that meets the definition of soil-pica used in this chapter. The second category probably does represent ingestion that would satisfy the definition of soil-pica as well as geophagy. The first category may represent relatively small amounts that appear to be ingested by many children based on the Hogan et al. (1998) study and the tracer element studies. Second, the U.S. tracer studies report a wide range of soil ingestion values. Due to averaging procedures used, for 4, 7, or 8 day periods, the rounded range of these estimates of soil ingestion behavior that apparently met the definition of soil-pica used in this chapter is from 400 to 41,000 mg/day. The recommendation of 1,000 mg/day for soil-pica is based on this range.

Although there were no tracer element studies or biokinetic model comparison studies performed for children 15 to <21 years, in which soil-pica behavior of children in this age range has been investigated, U.S. EPA is aware of one study documenting pica behavior in a group that includes children in this age range (Hyman et al., 1990). The study was not specific regarding whether soil-pica (versus other pica substances) was observed, nor did it identify the specific ages of the children observed to practice pica. In the absence of data that can be used to develop specific soil-pica soil ingestion recommendations for children aged 15 years and 16 to <21 years, U.S. EPA recommends that risk assessors who need to assess risks via soil and dust ingestion to children ages 15 to <21 years use the same soil ingestion rate as that recommended for younger children, in the 1 to <6, 6 to <11, and 11 to <16 year old age categories.

Researchers who have studied human geophagy behavior around the world typically have studied populations in specific locations, and often include investigations of soil properties as part of the research (Wilson, 2003; Aufreiter et al., 1997). Most studies of geophagy behavior in the United States were survey response studies of residents in specific locations who acknowledged eating clays. Typically, study subjects were from a relatively small area such as a county, or a group of counties within the same state. Although geophagy behavior may have been studied in only a single county in a given state, documentation of geophagy behavior by some residents in one or more counties of a given state may suggest that the same behavior also occurs elsewhere within that state.

A qualitative description of amounts of soil ingested by geophagy practitioners was provided by Vermeer and Frate (1979) with an estimated mean amount, 50 g/day, that apparently was averaged over 32 adults and 18 children. The 18 children whose caregivers acknowledged geophagy (or more specifically, eating of clay) were (*N* = 16) ages 1 to 4 and (*N* = 2) ages 5 to 12 years. The definition of geophagy used included consumption of clay "on a regular basis over a period of weeks." U.S. EPA is recommending this 50 g/day value for geophagy. This mean quantity is roughly consistent with a median quantity reported by Geissler et al. (1998) in a survey response study of geophagy in primary school children in Nyanza Province, Kenya (28 g/day, range 8 to 108 g/day; interquartile range 13 to 42 g/day).

Recent studies of pica among pregnant women in various U.S. locations (Corbett et al., 2003; Rainville, 1998; Smulian et al., 1995) suggest that clay geophagy among pregnant women may include children less than 21 years old (Corbett et al., 2003; Smulian et al., 1995). Smulian provides a quantitative estimate of clay consumption of approximately 200−500 g/week, for the very small number of geophagy practitioners (*N* = 4) in that study's sample (*N* = 125). If consumed on a daily basis, this quantity (approximately 30 to 70 g/day) is roughly consistent with the Vermeer and Frate (1979) estimated mean of 50 g/day.

Johns and Duquette (1991) describe use of clays in baking bread made from acorn flour, in a ratio of 1 part clay to 10 or 20 parts acorn flour, by volume, in a Native American population in California, and in Sardinia (~12 grams clay suspended in water added to 100 grams acorn). Either preparation method would add several grams of clay to the final prepared food; daily ingestion of the food would amount to several grams of clay ingested daily.

5.7. REFERENCES FOR CHAPTER 5

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Table 5-3. Soil, Dust, and Soil + Dust Ingestion Estimates for Amherst, Massachusetts Study Children

Tracer Element	*N*	Ingestion (mg/day)				
		Mean	Median	SD	95th Percentile	Maximum
Aluminum						
soil	64	153	29	852	223	6,837
dust	64	317	31	1,272	506	8,462
soil/dust combined	64	154	30	629	478	4,929
Barium						
soil	64	32	–37	1,002	283	6,773
dust	64	31	–18	860	337	5,480
soil/dust combined	64	29	–19	868	331	5,626
Manganese						
soil	64	–294	–261	1,266	788	7,281
dust	64	–1,289	–340	9,087	2,916	20,575
soil/dust combined	64	–496	–340	1,974	3,174	4,189
Silicon						
soil	64	154	40	693	276	5,549
dust	64	964	49	6,848	692	54,870
soil/dust combined	64	483	49	3,105	653	24,900
Vanadium						
soil	62	459	96	1,037	1,903	5,676
dust	64	453	127	1,005	1,918	6,782
soil//dust combined	62	456	123	1,013	1,783	6,736
Yttrium						
soil	62	85	9	890	106	6,736
dust	64	62	15	687	169	5,096
soil/dust combined	62	65	11	717	159	5,269
Zirconium						
soil	62	21	16	209	110	1,391
dust	64	27	12	133	160	789
soil/dust combined	62	23	11	138	159	838
Titanium						
soil	64	218	55	1,150	1,432	6,707
dust	64	163	28	659	1,266	3,354
soil/dust combined	64	170	30	691	1,059	3,597

SD = Standard deviation.
N = Number of subjects.

Source: Calabrese et al. (1989).

Table 5-4. Amherst, Massachusetts Soil-Pica Child's Daily Ingestion Estimates by Tracer and by Week (mg/day)

Tracer element	Estimated Soil Ingestion (mg/day) Week 1	Week 2
Al	74	13,600
Ba	458	12,088
Mn	2,221	12,341
Si	142	10,955
Ti	1,543	11,870
V	1,269	10,071
Y	147	13,325
Zr	86	2,695

Source: Calabrese et al. (1991).

Table 5-5. Van Wïjnen et al. (1990) Limiting Tracer Method (LTM) Soil Ingestion Estimates for Sample of Dutch Children

Age (years)	Sex	Daycare Center			Campground		
		N	GM LTM (mg/day)	GSD LTM (mg/day)	*N*	GM LTM (mg/day)	GSD LTM (mg/day)
Birth to <1	Girls	3	81	1.09	NA	NA	NA
	Boys	1	75		NA	NA	NA
1 to <2	Girls	20	124	1.87	3	207	1.99
	Boys	17	114	1.47	5	312	2.58
2 to <3	Girls	34	118	1.74	4	367	2.44
	Boys	17	96	1.53	8	232	2.15
3 to <4	Girls	26	111	1.57	6	164	1.27
	Boys	29	110	1.32	8	148	1.42
4 to <5	Girls	1	180		19	164	1.48
	Boys	4	99	1.62	18	136	1.30
All girls		86	117	1.70	36	179	1.67
All boys		72	104	1.46	42	169	1.79
Total		162[a]	111	1.60	78[b]	174	1.73

[a] Age and/or sex not registered for 8 children; one untransformed value = 0.
[b] Age not registered for 7 children; geometric mean LTM value = 140.
N = Number of subjects.
GM = Geometric mean.
LTM = Limiting tracer method.
GSD = Geometric standard deviation.
NA = Not available.

Source: Adapted from Van Wïjnen et al. (1990).

Table 5-6. Estimated Geometric Mean Limiting Tracer Method (LTM) Soil Ingestion Values of Children Attending Daycare Centers According to Age, Weather Category, and Sampling Period

Weather Category	Age (years)	First Sampling Period		Second Sampling Period	
		N	Estimated Geometric Mean LTM Value (mg/day)	*N*	Estimated Geometric Mean LTM Value (mg/day)
Bad	<1	3	94	3	67
(>4 days/week	1 to <2	18	103	33	80
precipitation)	2 to <3	33	109	48	91
	4 to <5	5	124	6	109
Reasonable	<1			1	61
(2−3 days/week	1 to <2			10	96
precipitation)	2 to <3			13	99
	3 to <4			19	94
	4 to <5			1	61
Good	<1	4	102		
(<2 days/week	1 to <2	42	229		
precipitation)	2 to <3	65	166		
	3 to <4	67	138		
	4 to <5	10	132		

N = Number of subjects.
LTM = Limiting tracer method.

Source: Van Wijnen et al. (1990).

Table 5-7. Estimated Soil Ingestion for Sample of Washington State Children[a]

Element	Mean (mg/day)	Median (mg/day)	Standard Error of the Mean (mg/day)	Range (mg/day)[b]
Aluminum	38.9	25.3	14.4	–279.0 to 904.5
Silicon	82.4	59.4	12.2	–404.0 to 534.6
Titanium	245.5	81.3	119.7	–5,820.8 to 6,182.2
Minimum	38.9	25.3	12.2	–5,820.8
Maximum	245.5	81.3	119.7	6,182.2

[a] Excludes three children who did not provide any samples (*N* = 101).
[b] Negative values occurred as a result of correction for non-soil sources of the tracer elements. For aluminum, lower end of range published as 279.0 mg/day in article appears to be a typographical error that omitted the negative sign.

Source: Adapted from Davis et al. (1990).

Table 5-8. Soil Ingestion Estimates for 64 Anaconda Children

Tracer	Estimated Soil Ingestion (mg/day)							
	p1	p50	p75	p90	p95	Max	Mean	SD
Al	–202.8	–3.3	17.7	66.6	94.3	461.1	2.7	95.8
Ce	–219.8	44.9	164.6	424.7	455.8	862.2	116.9	186.1
La	–10,673	84.5	247.9	460.8	639.0	1,089.7	8.6	1,377.2
Nd	–387.2	220.1	410.5	812.6	875.2	993.5	269.6	304.8
Si	–128.8	–18.2	1.4	36.9	68.9	262.3	–16.5	57.3
Ti	–15,736	11.9	398.2	1,237.9	1,377.8	4,066.6	–544.4	2,509.0
Y	–441.3	32.1	85.0	200.6	242.6	299.3	42.3	113.7
Zr	–298.3	–30.8	17.7	94.6	122.8	376.1	–19.6	92.5
BTM soil	NA	20.1	68.9	223.6	282.4	609.9	65.5	120.3
BTM dust	NA	26.8	198.1	558.6	613.6	1,499.4	127.2	299.1

p = Percentile.
SD = Standard deviation.
BTM = Best Tracer Methodology.
NA Not available.
Note: Negative values are a result of limitations in the methodology.

Source: Calabrese et al. (1997b).

Table 5-9. Soil Ingestion Estimates for Massachusetts Children Displaying Soil Pica Behavior (mg/day)

Study day	Al-based estimate	Si-based estimate	Ti-based estimate
1	53	9	153
2	7,253	2,704	5,437
3	2,755	1,841	2,007
4	725	534	801
5	5	–10	21
6	1,452	1,373	794
7	238	76	84

Note: Negative values are a result of limitations in the methodology.

Source: Calabrese et al. (1997a).

Table 5-10. Average Daily Soil and Dust Ingestion Estimate (mg/day)

Type of Estimate	Soil Ingestion			Dust Ingestion		
	Al	Si	Ti	Al	Si	Ti
Mean	168	89	448	260	297	415
Median	7	0	32	13	2	66
SD	510	270	1,056	759	907	1,032
Range	–15 to +1,783	–46 to +931	–47 to +3,581	–39 to +2,652	–351 to +3,145	–98 to +3,632

SD = Standard deviation.
Note: Negative values are a result of limitations in the methodology.

Source: Calabrese et al. (1997a).

Table 5-11. Mean and Median Soil Ingestion (mg/day) by Family Member

Participant	Tracer Element	Estimated Soil Ingestion[a] (mg/day)			Maximum
		Mean	Median	SD	
Child[b]	Aluminum	36.7	33.3	35.4	107.9
	Silicon	38.1	26.4	31.4	95.0
	Titanium	206.9	46.7	277.5	808.3
Mother[c]	Aluminum	92.1	0	218.3	813.6
	Silicon	23.2	5.2	37.0	138.1
	Titanium	359.0	259.5	421.5	1,394.3
Father[d]	Aluminum	68.4	23.2	129.9	537.4
	Silicon	26.1	0.2	49.0	196.8
	Titanium	624.9	198.7	835.0	2,899.1

[a] For some study participants, estimated soil ingestion resulted in a negative value. These estimates have been set to 0 mg/day for tabulation and analysis.
[b] Results based on 12 children with complete food, excreta, and soil data.
[c] Results based on 16 mothers with complete food, excreta, and soil data.
[d] Results based on 17 fathers with complete food, excreta, and soil data.
SD = Standard deviation.

Source: Davis and Mirick (2006).

Table 5-12. Estimated Soil Ingestion for Six High Soil Ingesting Jamaican Children

Child	Month	Estimated soil ingestion (mg/day)
11	1	55
	2	1,447
	3	22
	4	40
12	1	0
	2	0
	3	7,924
	4	192
14	1	1,016
	2	464
	3	2,690
	4	898
18	1	30
	2	10,343
	3	4,222
	4	1,404
22	1	0
	2	-
	3	5,341
	4	0
27	1	48,314
	2	60,692
	3	51,422
	4	3,782

\- = No data.

Source: Calabrese and Stanek (1993).

Table 5-13. Positive/Negative Error (bias) in Soil Ingestion Estimates in Calabrese et al. (1989) Study: Effect on Mean Soil Ingestion Estimate (mg/day)[a]

Tracer	Negative Error						
	Lack of Fecal Sample on Final Study Day	Other Cause[b]	Total Negative Error	Total Positive Error	Net Error	Original Mean	Adjusted Mean
Aluminum	14	11	25	43	+18	153	136
Silicon	15	6	21	41	+20	154	133
Titanium	82	187	269	282	+13	218	208
Vanadium	66	55	121	432	+311	459	148
Yttrium	8	26	34	22	–12	85	97
Zirconium	6	91	97	5	–92	21	113

[a] How to read table: for example, aluminum as a soil tracer displayed both negative and positive error. The cumulative total negative error is estimated to bias the mean estimate by 25 mg/day downward. However, aluminum has positive error biasing the original mean upward by 43 mg/day. The net bias in the original mean was 18 mg/day positive bias. Thus, the original 156 mg/day mean for aluminum should be corrected downward to 136 mg/day.

[b] Values indicate impact on mean of 128-subject-weeks in milligrams of soil ingested per day.

Source: Calabrese and Stanek (1995).

Table 5-14. Predicted Soil and Dust Ingestion Rates for Children Age 3 to <6 Years (mg/day)

		Mean	Percentile					
			5	25	50	75	95	100
Dust ingestion/hand-to-mouth	1,000	19.8	0.6	3.4	8.4	21.3	73.7	649.3
Dust ingestion/ object-to-mouth	1,000	6.9	0.1	0.7	2.4	7.4	27.2	252.7
Total dust ingestion[a]	1,000	27			13		109	360
Soil ingestion/hand-to-mouth	1,000	41.0	0.2	5.3	15.3	44.9	175.6	1,367.4
Total ingestion	1,000	67.6	4.9	16.8	37.8	83.2	224.0	1,369.7

[a] Email from Haluk Özkaynak (NERL, U.S. EPA) to Jacqueline Moya (NCEA, EPA) dated 3/8/11.

Source: Özkaynak et al. (2011).

Table 5-15. Estimated Daily Soil Ingestion for East Helena, Montana Children

Estimation Method	Mean (mg/day)	Median (mg/day)	Standard Deviation (mg/day)	Range (mg/day)	95th Percentile (mg/day)	Geometric Mean (mg/day)
Aluminum	181	121	203	25−1,324	584	128
Silicon	184	136	175	31−799	578	130
Titanium	1,834	618	3,091	4−17,076	9,590	401
Minimum	108	88	121	4−708	386	65

Source: Binder et al. (1986).

Table 5-16. Estimated Soil Ingestion for Sample of Dutch Nursery School Children

Child	Sample Number	Soil Ingestion as Calculated from Ti (mg/day)	Soil Ingestion as Calculated from Al (mg/day)	Soil Ingestion as Calculated from AIR (mg/day)	Limiting Tracer (mg/day)
1	L3	103	300	107	103
	L14	154	211	172	154
	L25	130	23	-	23
2	L5	131	-	71	71
	L13	184	103	82	82
	L27	142	81	84	81
3	L2	124	42	84	42
	L17	670	566	174	174
4	L4	246	62	145	62
	L11	2,990	65	139	65
5	L8	293	-	108	108
	L21	313	-	152	152
6	L12	1,110	693	362	362
	L16	176	-	145	145
7	L18	11,620	-	120	120
	L22	11,320	77	-	77
8	L1	3,060	82	96	82
9	L6	624	979	111	111
10	L7	600	200	124	124
11	L9	133	-	95	95
12	L10	354	195	106	106
13	L15	2,400	-	48	48
14	L19	124	71	93	71
15	L20	269	212	274	212
16	L23	1,130	51	84	51
17	L24	64	566	-	64
18	L26	184	56	-	56
Arithmetic Mean		1,431	232	129	105

\- = No data.
AIR = Acid insoluble residue.

Source: Adapted from Clausing et al. (1987).

Table 5-17. Estimated Soil Ingestion for Sample of Dutch Hospitalized, Bedridden Children

Child	Sample	Soil Ingestion as Calculated from Ti (mg/day)	Soil Ingestion as Calculated from Al (mg/day)	Limiting Tracer (mg/day)
1	G5	3,290	57	57
	G6	4,790	71	71
2	G1	28	26	26
3	G2	6,570	94	84
	G8	2,480	57	57
4	G3	28	77	28
5	G4	1,100	30	30
6	G7	58	38	38
Arithmetic Mean		2,293	56	49

Source: Adapted from Clausing et al. (1987).

Table 5-18. Items Ingested by Low-Income Mexican-Born Women Who Practiced Pica During Pregnancy in the United States (*N* = 46)

Item Ingested	Number (%) Ingesting Items
Dirt	11 (24)
Bean stones[a]	17 (37)
Magnesium carbonate	8 (17)
Ashes	5 (11)
Clay	4 (9)
Ice	18 (39)
Other[b]	17 (37)

[a] Little clods of dirt found among unwashed beans.
[b] Including eggshells, starch, paper, lipstick, pieces of clay pot, and adobe.
N = Number of individuals reporting pica behavior.

Source: Simpson et al. (2000).

Table 5-19. Distribution of Average (mean) Daily Soil Ingestion Estimates per Child for 64 Children[a] (mg/day)

Type of Estimate	Overall	Al	Ba	Mn	Si	Ti	V	Y	Zr
Number of Samples	64	64	33	19	63	56	52	61	62
Mean	179	122	655	1,053	139	271	112	165	23
25th Percentile	10	10	28	35	5	8	8	0	0
50th Percentile	45	19	65	121	32	31	47	15	15
75th Percentile	88	73	260	319	94	93	177	47	41
90th Percentile	186	131	470	478	206	154	340	105	87
95th Percentile	208	254	518	17,374	224	279	398	144	117
Maximum	7,703	4,692	17,991	17,374	4,975	12,055	845	8,976	208

[a] For each child, estimates of soil ingestion were formed on days 4–8 and the mean of these estimates was then evaluated for each child. The values in the column "overall" correspond to percentiles of the distribution of these means over the 64 children. When specific trace elements were not excluded via the relative standard deviation criteria, estimates of soil ingestion based on the specific trace element were formed for 108 days for each subject. The mean soil ingestion estimate was again evaluated. The distribution of these means for specific trace elements is shown.

Source: Stanek and Calabrese (1995a).

Table 5-20. Estimated Distribution of Individual Mean Daily Soil Ingestion Based on Data for 64 Subjects Projected Over 365 Days[a]	
Range	1−2,268 mg/day[b]
50th Percentile (median)	75 mg/day
90th Percentile	1,190 mg/day
95th Percentile	1,751 mg/day

[a] Based on fitting a lognormal distribution to model daily soil ingestion values.
[b] Subject with pica excluded.

Source: Stanek and Calabrese (1995a).

Table 5-21. Prevalence of Non-Food Consumption by Substance for NHANES I and NHANES II

	NHANES I (age 1−74 years) *N* (sample size) = 20,724 (unweighted); 193,716,939 (weighted)			NHANES II (age 6 months−74 years) *N* (sample size) = 25,271 (unweighted); 203,432,944 (weighted)		
Substance	*N* Unweighted (Weighted)	Prevalence[a]	95% Confidence Interval	*N* Unweighted (Weighted)	Prevalence[a]	95% Confidence Interval
Any Non-Food Substance	732 (4,900,370)	2.5%	2.2−2.9%	480 (2,237,993)	1.1%	1.0−1.2%
Clay				46 (223,361)	0.1%	0.1−0.2%
Starch	131 (582,101)	0.3%	0.2−0.4%	61 (450,915)	0.2%	0.1−0.3%
Paint and Plaster	39 (195,764)	0.5%[b]	0.3−0.7%	55 (213,588)	0.6%[c]	0.4−0.8%
Dirt				216 (772,714)	2.1%[d]	1.7−2.5%
Dirt and Clay	385 (2,466,210)	1.3%	1.1−1.5%			
Other	190 (1,488,327)	0.8%	0.6−0.9%	218 (1,008,476)	0.5%	0.4−0.6%

Unweighted = Raw counts.
Weighted = Adjusted to account for the unequal selection probabilities caused by the cluster design, item non-response, and planned oversampling of certain subgroups, and representative of the civilian non-institutionalized Census population in the coterminous United States.
[a] Prevalence = Frequency (*n*) (weighted)/Sample Size (*N*) (weighted).
[b] NHANES I sample size (<12 years): 4,968 (unweighted); 40,463,951 (weighted).
[c] NHANES II sample size (<12 years): 6,834 (unweighted); 37,697,059 (weighted).
[d] For those aged <12 years only; question not prompted for those ≥12 years.

Source: Gavrelis et al. (2011).

Table 5-22. Summary of Estimates of Soil and Dust Ingestion by Adults and Children (0.5 to 14 years old) From Key Studies (mg/day)

Sample Size	Age (year)	Ingestion medium	Mean	p25	p50	p75	p90	p95	Reference
140	1 to13+	Soil	50,000[a]	NR	NR	NR	NR	NR	Vermeer and Frate (1979)
89	Adult	Soil	50,000[a]	NR	NR	NR	NR	NR	Vermeer and Frate (1979)
52	0.3 to14	Soil	NR	NR	NR	NR	~1,267	~4,000	Wong (1988); Calabrese and Stanek (1993)
64	1 to <4	Soil Dust Soil and Dust	−294 to +459 −1,289 to +964 −496 to +483	NR NR NR	−261 to +96 −340 to +127 −340 to +456	NR NR NR	67 to 1,366 91 to 1,700 89 to 1,701	106 to 1,903 160 to 2,916 159 to 3,174	Calabrese et al. (1989)
292	0.1 to <1 1 to <5	Soil Soil	0 to 30[b] 0 to 200[b]	NR NR	NR NR	NR NR	NR ≤300	NR NR	Van Wijnen et al. (1990)
101	2 to <8	Soil Soil and Dust	39 to 246 65 to 268	NR NR	25 to 81 52 to 117	NR NR	NR NR	NR NR	Davis et al. (1990)
64	1 to <4	Soil	97 to 208	NR	NR	NR	NR	NR	Calabrese and Stanek (1995)
165	1 to <8	Soil	104	NR	37	NR	NR	217	Stanek and Calabrese (1995b)
64	1 to <4	Soil	−544 to +270	−582to +65	−31 to +220	1 to 411	37 to 1,238	69 to 1,378	Calabrese et al. (1997b)
478	<1 to <7	Soil and Dust	113	NR	NR	NR	NR	NR	Hogan et al. (1998)
33	Adult	Soil	23 to 625	NR	0 to 260	NR	NR	138 to 2,899	Davis and Mirick (2006)
12	3 to <8	Soil	37 to 207	NR	26 to 47	NR	NR	95 to 808	Davis and Mirick (2006)
1,000[c]	3 to <6	Soil Dust Soil and Dust	41 27 68	5.3 NR 16.8	15.3 13 37.8	44.9 NR 83.2	NR NR NR	175.6 109 224	Özkaynak et al. (2011)

a Average includes adults and children.
b Geometric mean.
c Simulated.
NR = Not reported.
p = Percentile.

Table 5-23. Comparison of Hogan et al. (1998) Study Subjects' Predicted Blood Lead Levels With Actual Measured Blood Lead Levels, and Default Soil + Dust Intakes Used in IEUBK Modeling

Age (year)	*N*	*N* prediction >actual	*N* prediction <actual	time-averaged default soil + dust intake (mg/day)
1 and 2	164	14	150	135
3 and 4	142	104	38	117.5
5 and 6	134	0	134	87.5
Average				113

N = Number.

Source: Adapted from Hogan et al. (1998).

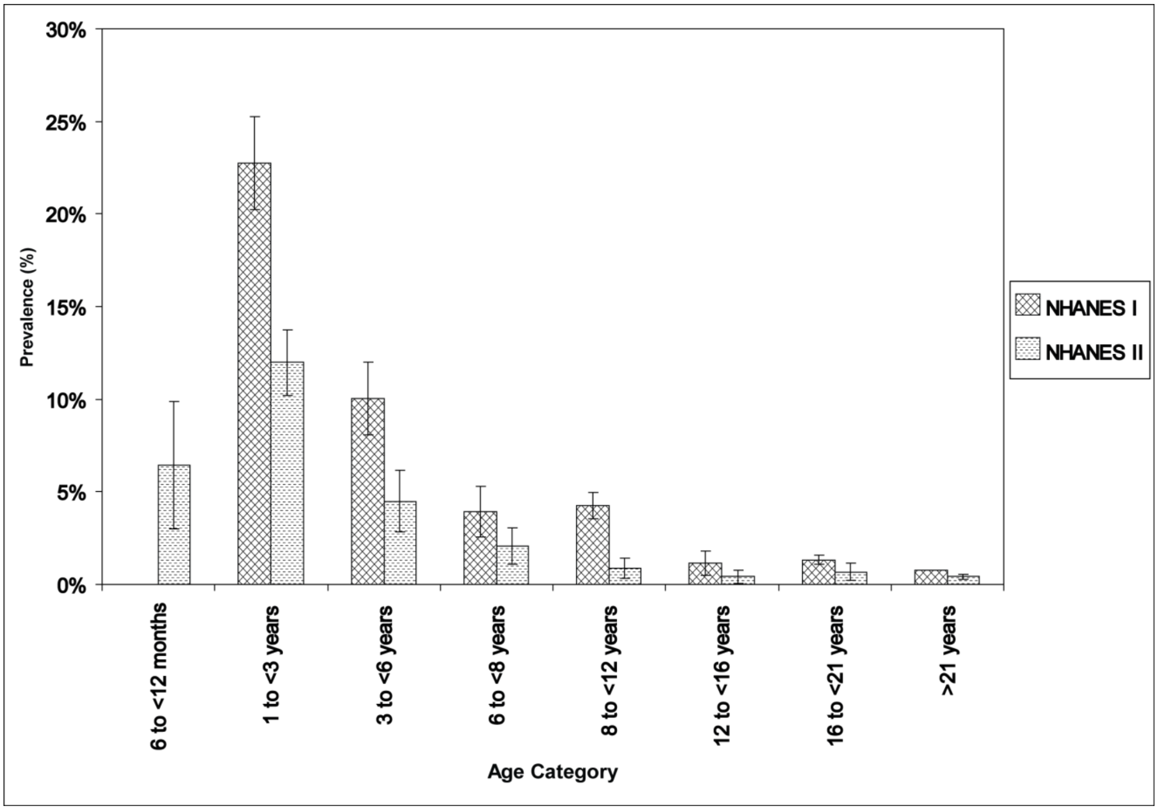

Figure 5-1. Prevalence of Non-Food Substance Consumption by Age, NHANES I and NHANES II.

Source: Gavrelis et al. (2011).

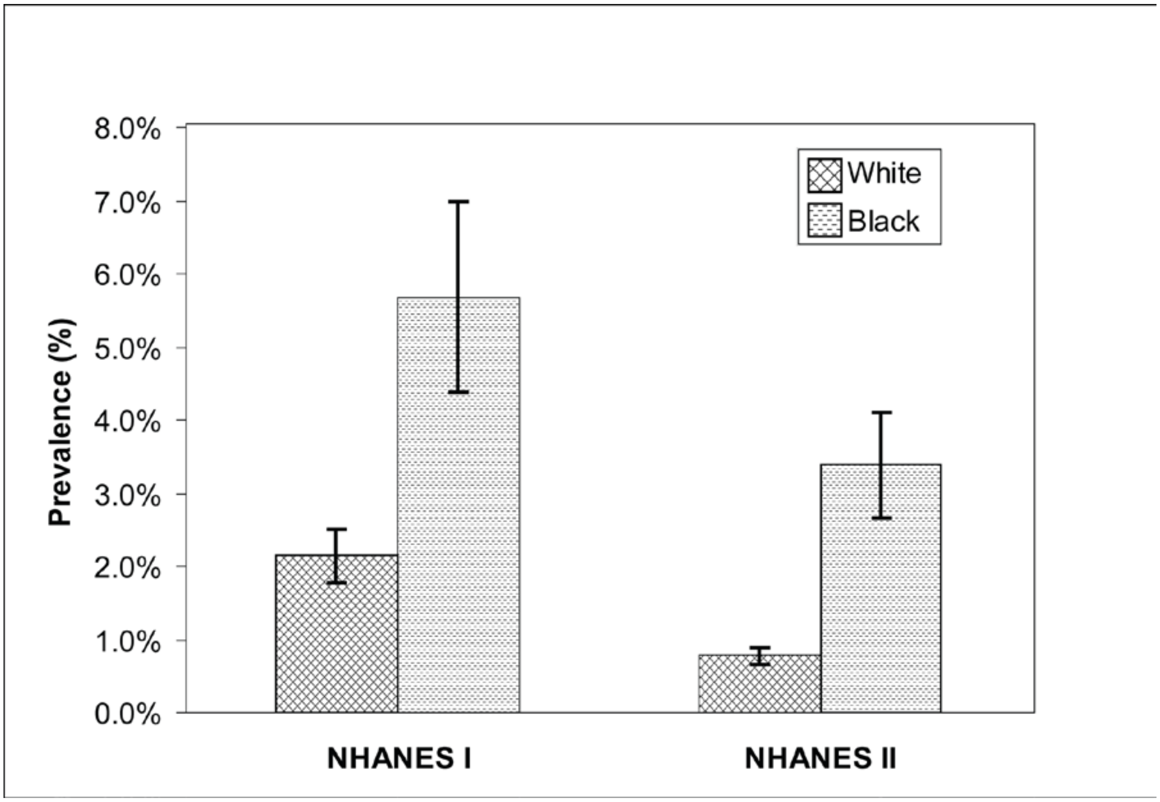

Figure 5-2. Prevalence of Non-Food Substance Consumption by Race, NHANES I and NHANES II.

Source: Gavrelis et al. (2011).

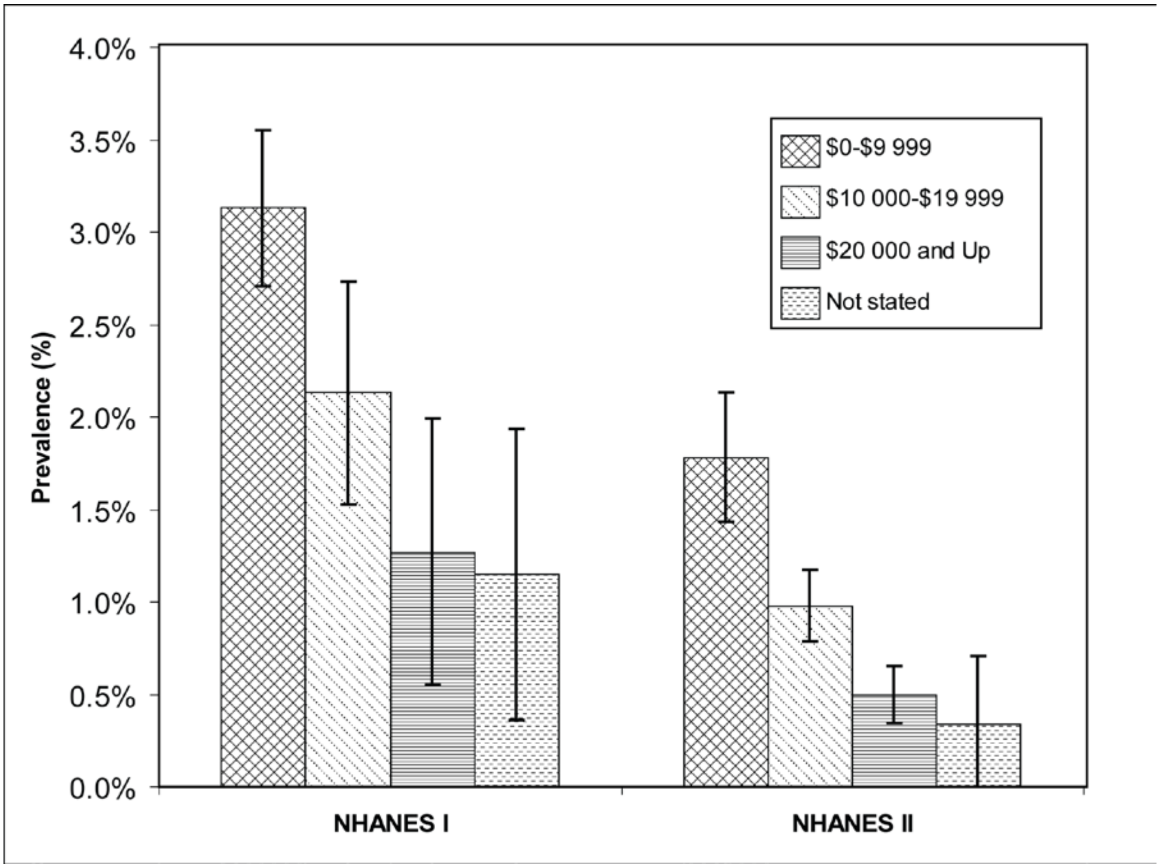

Figure 5-3. Prevalence of Non-Food Substance Consumption by Income, NHANES I and NHANES II.

Source: Gavrelis et al. (2011).