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Soil ingestion in children and adults in the same family

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Ingestion of soil may be a potentially important pathway of exposure to environmental pollutants. Although several studies have estimated soil ingestion in children, data on ingestion in adults are sparse. The purposes of this study were to estimate soil ingestion in children aged 3 to 8 years and their parents, identify factors associated with increased ingestion, and compare ingestion rates within the same family. Food/liquid, excreta, and soil/dust samples were collected for the mother, father, and participant child for 11 consecutive days in 19 families. Soil ingestion was estimated using a mass balance approach. Soil ingestion levels in children were similar to those reported previously, whereas adult estimates were somewhat higher than previous estimates. Children's eating of dirt and parents' occupational contact with soil were associated with increased ingestion. Within families, soil ingestion levels in children and adults were not correlated, although this analysis was based on fewer than 19 participant families. Children's mean soil ingestion rates ranged from 37 to 207 mg/day depending on the tracer, with the highest values based on titanium as a tracer. Adult mean soil ingestion rates ranged from 23 to 625 mg/day depending on the tracer, with the highest value based on titanium as a tracer. Soil ingestion rate estimates were more variable in adults than in children.
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Introduction

Ingestion of soil and dust particles may be a potentially important pathway of exposure to environmental pollutants, both in children and adults, via recreational activities, gardening, consumption of locally grown foods, and ingestion of airborne dust. While adults may also ingest soil via occupational exposure, it is generally assumed that child ingestion rates are higher than adult rates, due primarily to children's mouthing behaviors. A number of studies have attempted to estimate soil ingestion in children (Binder et al., 1986; Clausing et al., 1987; Wong et al., 1988; Calabrese et al., 1989; Davis et al., 1990; van Wijnen et al., 1990; Calabrese et al., 1991; Stanek and Calabrese, 1995; Calabrese et al., 1997a, b), whereas estimates of adult ingestion are limited and based on relatively few participants (Calabrese et al., 1990; Stanek et al., 1997). No study to date has attempted to estimate soil ingestion in both children and their parents, which would allow for meaningful comparisons between adult and child ingestion rates while controlling for other factors that could affect ingestion estimates, such as contaminants and pollutants around the home environment, hygiene practices and food choices that are unique to a given family, and recreational activities shared by family members.

This study had several primary aims: (1) to estimate the rate of soil ingestion during normal activities in the mother, father, and participant child of 20 families; (2) to identify behavioral and lifestyle factors potentially related to soil ingestion values in children and adults; (3) to compare adult and child soil ingestion estimates within the same family; and (4) to compare ingestion estimates between the male and female parent or guardian of the same family. The data collected from the adults at the time of fieldwork constituted the first obtained from a systematic investigation of this type in the US. A secondary aim of the study was to substantially refine existing field methods used to collect data of the type required for ingestion estimates, potentially improving existing estimates of soil ingestion values in young children.

Materials and methods

Participant families were a subset of those who completed a previous study of soil ingestion in children conducted by the investigative team 1 year prior to the current study (Davis et al., 1990). Briefly, the previous study involved 104 children between the ages of 2 and 7 years, selected randomly from the tri-city area of Richland, Pasco, and Kennewick, located in the arid, southeastern portion of Washington State. A duplicate of all food items consumed, all feces excreted,

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twice-daily urine samples, soil, and house dust were collected and analyzed for the presence of aluminum, silicon, and titanium tracer elements. Soil ingestion was calculated using a mass balance approach. Study methods and results are described elsewhere in more detail (Davis et al., 1990). For the present study, a subset of 20 families from the original 104 was chosen based on the following criteria: (1) they were highly compliant with the previous study protocol, (2) they expressed a willingness to participate in a future study, (3) the participant child would be less than 8 years old at the time of fieldwork, and (4) both a male and female parent or guardian were living at home with the participant child. Thus, a participant family consisted of the original child participant, the female, and the male parent or guardian living in the same house. The 20 families were selected without regard to the results from the first study (i.e., selection was not based on the child's previous estimated soil ingestion). However, study data were missing for one of the families. Therefore, analysis was completed for the remaining 19 families.

Data Collection

Overview Data collection took place during the summer of 1988, and consisted of several components over a 14-day period. Families were encouraged to avoid overnight, out-of-town travel during their involvement. Each family received $500 for completing the study. A short in-person interview was administered on day 1 of participation. The purpose of the interview was to collect information about the child's and parents' food and dietary habits, personal habits, occupational information, and family demographics. Beginning on the second day of the study, a duplicate sample of all food and non-food items consumed for 11 consecutive 24-h days were collected for all three family members. Excreta was collected for 11 consecutive days, beginning on day 3 of the study (offset by 24 h from the food ingestion period). Parents completed a daily diary of activities for themselves and the participant child for four consecutive days. The field technician collected soil samples based on information provided in the daily activity diary, as well as household dust samples from the residence of each family.

The Fred Hutchinson Cancer Research Center Institutional Review Board approved the procedures for contacting potential participants, obtaining informed consent, and all data collection procedures, and both parents of each participant child signed written informed consent before participation.

Food and Liquid Collection and Processing Duplicate samples of all food and non-food items (except for water) consumed for 11 consecutive days were collected separately for each of the three family members. A "day" was defined as the period between midnight and 2359 hours, 24 h later. Parents were given specific instructions for collecting certain types of foods, such as frozen foods and candy, and were instructed to not collect inedible parts of foods (e.g., banana peels, chicken bones, food wrappers). A duplicate sample of any meals taken away from home, such as in a restaurant or at daycare, was to be included as well. A single sample of any vitamin, food supplement, or medication (over-the-counter or prescription) taken by mouth or as a suppository was collected and labeled with the participant identification number. Parents recorded the amount taken during each 24-h period. For each food collection day, parents were instructed to list any food or liquid consumed that was not contained in the duplicate sample (i.e., a missed item) and to estimate the amount of the item consumed.

The 24-h food and liquid samples were collected daily by the field technician and delivered to Battelle Pacific Northwest Laboratories (Richland, Washington), where they were stored in a laboratory refrigerator until processing. Processing occurred immediately upon completion of sample collection. Food/liquid samples were combined into two time periods, from the first 4 days (study days 2–5) and last 7 days of sample collection (days 6–12), and homogenized in a stainless steel blender. Weighted aliquots from each of the two time periods was dried in a forced air oven at 80–100°C for 72 h and ashed in platinum crucibles in a furnace at 900°C–1000°C for 16–24 h. Once cooled, the ashed sample was weighed and pulverized to a fine powder in a mortar, and was then pressed into a undiluted thin wafer of approximately 50 mg/cm^2 thickness before storing for chemical analysis (described below). Prescription and over-the-counter medications and vitamins were submitted for analysis in their original form.

Excreta Collection and Processing Offset by 24 h from the food ingestion period, excreta was collected beginning on day 3 of the study in the following manner: (1) all feces for 11 consecutive days, (2) first morning and last evening void of urine, as well as all urine excreted during the night, for 9 consecutive days, and (3) complete 24-h urine volume for 2 consecutive days. Samples from each participant family member and each day were kept separate from one another. As for the food/liquid collection, a "day" was defined as the period between midnight and 2359 hours, 24 h later. As much as possible, urine and feces samples were to be collected and kept separate from one another. Parents were provided with toilet-mounted collection devices to facilitate excreta collection. Each day, parents were instructed to indicate the number of samples collected and the number of samples missed on a daily excreta collection form for each participant family member.

Urine and fecal samples were collected daily by the field technician and delivered to Battelle, where they were weighed and stored in a laboratory refrigerator until processing. Processing occurred immediately upon completion of excreta collection. Since daily urine samples for each participant were often in multiple containers, samples were combined prior to weighing and storing. Once sample collection was complete, urine samples for each participant were consolidated into four time periods as follows: (1) the first 4 days of sample collection (study days 3–6), (2) the next 5 days (days 7–11), (3) the first 24-h collection (day 12), and (4) the last 24-h urine collection (day 13). Once combined, urine samples were homogenized by thoroughly mixing with a stir-bar. Each combined urine sample was weighed and transferred to a crystallizing dish, and evaporated to hygroscopic syrup in an oven at 80–100°C. These semidry samples were ashed and stored for chemical analysis (described below). Similarly, daily fecal samples were combined into one container prior to weighing if there was more than one sample for a given participant and day. Once sample collection was complete, fecal samples were consolidated into two time periods, from the first 4 days (study days 3–6) and the last 7 days of sample collection (days 7–13). As for the food/liquid samples, weighed aliquots from each of the two time periods were dried in a forced air oven at 80°C–100°C for 72 h and ashed in platinum crucibles in a furnace at 900°C–1000°C for 16–24 h. Once cooled, the ashed sample was weighed and pulverized to a fine powder in a mortar, and was then pressed into a undiluted thin wafer of approximately 50 mg/cm^2 thickness before storing for analysis.

Daily Activity Diary Participants completed a daily activities form for 4 consecutive days, beginning on study day 4. Both the child's and parents' forms collected information about time spent indoors and outdoors at home and away from home during the 24-h period of interest (i.e., between midnight and 2359 hours, 24 h later). The child's form asked specific questions regarding contact with dirt or soil in both the family yard as well as time spent away from home, and whether the child ate or drank while sitting on the ground. The adult's form addressed time spent indoors performing household chores (e.g., vacuuming, dusting, etc.) and outside doing various house and yard maintenance (e.g., gardening, sweeping, etc.). In addition to these questions, parents were asked to assist the field technician in drawing a diagram of the yard, in order to collect soil samples from those areas where each study participant played or spent the most time around the house and yard (see below).

Household Dust Sampling On day 5 of participation, the field technician collected household dust samples from the residence of each family, using a standardized collection procedure to ensure uniformity among the samples. A hand-held vacuum cleaner fitted with filter paper was used to collect dust samples from floors both with and without carpeting, from four rooms of the house: (1) the participant child's bedroom, (2) the parents' bedroom, (3) the principal living area of the house, and (4) kitchen. Each room was vacuumed for approximately 3 min. The field technician vacuumed bare floors rather than carpeting whenever possible, and focused on areas where the child was most likely to be in direct contact with the surface. Once several millimeters of dust had accumulated on the filter paper, it was removed using rubber gloves and forceps and placed in a clean glass vial. Additionally, a large sample of household dust was obtained from the participant family's own vacuum cleaner. If the family did not own a vacuum cleaner, the interviewer obtained a vacuum sample by using the same hand-held vacuum without the filter paper.

Household dust samples were delivered by the field technician to Battelle, where they were promptly washed from the filter paper using a dilute 0.1 N nitric acid solution. Samples were then dried in a ventilated drying oven for at least 24 h and stored. Dust samples from the home vacuum cleaner were passed successively through 20- and 60-mesh stainless-steel sieves to remove foreign material before storage.

Soil Sampling On day 12 of participation, soil samples were collected from the areas around the house where each individual family member spent time, as determined from the 4-day daily activity diary for each individual, and pooled in a manner proportional to the amount of time spent in the various locations that were sampled. Both surface and core soil samples were collected. Surface samples were collected using a hand-held vacuum cleaner. At each location identified by the participant as having spent time, the surface was vacuumed for 1 s per percentage point of time spent at that location. A different vacuum bag was used for each participant family member. Five core samples were collected at each location identified by the participant as having spent time, using a soil-coring device that was hammered into the ground to remove a plug of the soil 1 in^3 in size at a depth of approximately 3 in. Samples were collected at the four corners of a square area 3 yards by 3 yards, as well as the point where the diagonals of the area intersect, and consolidated into one sample for that location. Each sample was labeled with the percentage of time spent at that location, so that all the samples for a given participant could be pooled proportionally to the time spent at each location. No samples were collected away from the home area.

Soil samples were delivered by the field technician to Battelle, where they were promptly dried in a ventilated drying oven at approximately 125°C for several days. The dried samples were then passed successively through 20- and 60-mesh stainless-steel sieves in order to remove pebbles, grass, and roots before storage.

Chemical Analysis Upon completion of all data collection and sample processing, food/liquid, medications, feces, urine, soil, and house dust samples were stored at Battelle, Richland until funds were made available for chemical analyses. In 2000, the samples were transferred to Battelle Marine Sciences Laboratory (Sequim, Washington) for analysis. After digestion with an acid mixture, all sample types were analyzed for concentrations of silicon (Si), aluminum (Al), and titanium (Ti) using inductively coupled plasma-atomic emission spectrometry (ICP-AES) and inductively coupled plasma-mass spectrometry (ICP-MS).

For all sample types, quality control samples were analyzed with the study samples, including (1) laboratory control samples (LCS) with known concentrations of tracer elements of interest (food, feces, urine, medication) or standard reference material (SRM; soil, house dust), (2) matrix spike samples that were spiked in duplicate with known concentrations of the tracer elements (MS/MSD), and (3) duplicate digestions of some samples. Recoveries for most analyses were within the quality control limits of $\pm 20\%$ for the LCS or SRM and duplicate digestions, and $\pm 25\%$ for the MS/MSD. Initial and continuing calibration verification standards of the ICP-AES and ICP-MS instruments were within $\pm 15\%$ of the true value of each calibration standard for all metals.

Statistical Methods A mass balance approach was used to estimate daily soil ingestion values for each participant family member. Ideally, this method requires that a person's total intake and output be collected in a complete fashion, and that all collected samples be analyzed for tracer elements. Sample data were more complete when limited to the last 7 days of data collection (see below). Therefore, in order to maximize the accuracy of the final soil ingestion determination, all soil ingestion estimates and results are based on samples collected on these final 7 days, which includes study days 6 through 12 for food/liquid samples and days 7 through 13 for excreta samples. In this manner, the 24-h offset between collection of food/liquid and excreta samples is preserved. Soil ingestion was calculated in three different ways, by using core soil, surface soil, or household dust as the source of the ingested soil. For participant i and tracer element E, soil ingestion is calculated as:

$$S_{i,E} = \frac{((Wt_f \times ADJ_f \times E_f) + \sum_j (Wt_{\text{uj}} \times ADJ_{\text{umj}} \times ADJ_{u24j} \times E_{uj})) - ((Wt_{fd} \times E_{fd}) + (Wt_{md} \times E_{md}))}{E_{\text{soil/dust}} \times 10,000} \quad (1)$$

where: $S_{i,E}$ = soil ingested (g) for participant i based on tracer E; Wt_f = feces dry weight (g), ADJ_f = adjustment for missing fecal samples, E_f = measured tracer concentration in feces (μg/g); Wt_{uj} = urine dry weight (g) for urine collection period j, $\text{ADJ}_{\text{um}j}$ = adjustment for missing urine samples in collection period j, $\text{ADJ}_{\text{u}24j}$ = adjustment factor to estimate 24-h urine weight during twice-daily urine samples (days 7–11 only), E_uj = measured tracer concentration in urine (μg/g) in collection period j; Wt_fd = food/liquid dry weight (g), E_fd = measured tracer concentration in food/liquid (μg/g), Wt_md = medication dry weight (g), E_md = measured tracer concentration in medication (μg/g), and $E_\text{soil/dust}$ = measured tracer concentration in core soil, surface soil, or household dust (% weight, multiplied by 10,000 to convert to units of μg/g). For the 5 days of data collection in which urine samples were collected twice daily (days 7–11), an adjustment factor was calculated to estimate 24-h urine weight during these days (ADJ_u24j in the above equation), using actual 24-h urine weight from the 24-h collection periods (days 12 and 13). In order to account for missing fecal samples (ADJ_f in the above equation), the fecal dry weight was multiplied by a ratio of the number of fecal samples that should have been collected (i.e., the number collected + the number missed) to the number that was actually collected. This adjustment increased the fecal dry weight in proportion to the number of samples missed. A comparable adjustment was made to account for missing urine samples (ADJ_umj in the above equation). Collection of food/liquid samples was complete, and therefore no adjustment for missing samples was necessary.

Soil ingestion was calculated and analyzed for the final 7 days of data collection only. Total soil ingestion values were divided by seven to reflect average daily values, and units were converted to mg/day. In some instances, the soil ingestion calculation for an individual produced a negative estimate (i.e., amount of tracer in food + medication > amount of tracer in feces + urine). For these cases, the ingestion estimate was set to 0 mg/day for tabulation and analysis.

Results

Study data were missing for one of the original 20 participant families. All of the remaining 19 families completed the in-person interview, and the mother, father, and participant child of each family completed the daily diary of activities for all 4 days. Table 1 displays selected characteristics of participant children and their parents, based on responses to the in-person interview. Nearly two-thirds of participant children were male and more than 70% were aged 5 years and older. In 17 of 19 families, the responding parent (i.e., the person who completed the in-person interview) was the mother. The majority of both mothers and fathers completed at least some college. Of the mothers, most (13 of 19) were homemakers, whereas the fathers' occupations were varied with no clear tendency towards blue- or white-collar occupations. Slightly more than 60% had annual family incomes under \$30,000 (in 1988). One mother identified herself as Native American; all other parents identified themselves as Caucasian.

Responses to selected questions from the in-person interview regarding hygiene and eating behaviors are presented in

Table 1. Selected characteristics of participant children and respondent parents, Soil Ingestion Study.

Characteristic	No.	(%)[a]
Participant child		
Sex		
Male	12	(63.2)
Female	7	(36.8)
Age (years)		
3	2	(10.5)
4	3	(15.8)
5	4	(21.0)
6	5	(26.3)
7	5	(26.3)
Responding parent[b]		
Mother	17	(89.5)
Father	2	(10.5)
Highest level of education (completed)		
Mother		
<12 years	2	(10.5)
High school graduate	4	(21.0)
Some college	10	(52.6)
College graduate	2	(10.5)
Post-graduate study	1	(5.3)
Father		
<12 years	0	—
High school graduate	2	(10.5)
Some college	10	(52.6)
College graduate	3	(15.8)
Post-graduate study	4	(21.0)
Current occupation		
Mother		
Managerial/professional	3	(15.8)
Technical	2	(10.5)
Service	1	(5.3)
Farming	0	—
Production/laborers	0	—
Homemaker	13	(68.4)
Father		
Managerial/professional	5	(26.3)
Technical	4	(21.0)
Service	2	(10.5)
Farming	1	(5.3)
Production/laborers	6	(31.6)
Homemaker	1	(5.3)
Family income (annual)[c]		
<\$15,000	3	(15.8)
\$15,000—\$30,000	9	(47.4)
\$30,000–\$45,000	6	(31.6)
>\$45,000	1	(5.3)

[a]Percentage calculated from total number of participant families ($n = 19$).
[b]Parent who completed the in-person interview.
[c]For the year preceding data collection (1987).

Table 2. Most study participants brushed their teeth at least once per day and washed their hands, but not their faces, before meals. None of the families reported eating food or drinking liquids that were prepared, served, or stored in homemade or imported clay pottery; the participant child of one family consumed a food or liquid that had been stored in a previously opened tin or aluminum container once during the past week (data not shown). Few families reported consuming unwashed vegetables, fruits, or berries either from a family owned yard or garden or from another location such as a neighbor's yard or a store.

Responses to questions from the in-person interview regarding the participant child's mouthing behavior are shown in Table 3. Most responding parents (16 of 19) reported that their child does not suck his/her thumb or fingers. Of 19 children, 11 carry around a favorite blanket or toy; of these, only two take the item outside or put the item in their mouths. All but one child take food or liquid outside. Most participant children (16 of 19) do not mouth furniture or windowsills, but more than half of the children (58%) swallow dirt at least once per week.

Table 4 presents responses to questions regarding parents' (respondent and spouse) occupational and recreational behaviors that potentially involve contact with soil. More mothers than fathers reported occupational contact with soil for at least 1 h/week (47 *versus* 26%). However, four of 19 fathers reported contact with soil for at least 20 h/week during work. Nearly all parents reported at least 1 h/week of yard work (36 of 38), and most parents (30 of 38) reported participating in outdoor recreational activities involving contact with soil or dirt. Regarding indoor activities potentially involving contact with soil, all 19 mothers reported doing housework every week, and 21% (four of 19) reported engaging in some type of remodeling or indoor carpentry. In contrast, 47% (nine of 19) of fathers did at least some housework during the week and 42% (eight of 19) did some remodeling or carpentry every week.

The completeness of collection and laboratory analyses of food, excreta, soil, and dust samples for the final 7 days of sample collection are presented in Table 5. All of the participant children's urine samples from the first 4 days of data collection were unavailable for laboratory analysis, and therefore all analyses were limited to the final 7 days of data collection. Collection and chemical analyses of food/liquid samples for the mother, father, and participant child was complete for all 19 families. Overall, children's urine collection was less complete than that of mothers and fathers. For urine collection on days 7–11 (twice-daily collection), 10 of 19 children provided complete samples (i.e., no collections missed and no incomplete collections). Chemical analyses were conducted on some samples that were missing at least part of the urine sample. Therefore, laboratory results were available for two of the nine incomplete children's samples from days 7–11, for a total of 12 samples. Similarly, for both mothers and fathers, 15 of 19 collected complete samples for days 7–11, but results of chemical analyses were available for 18 of 19. The two 24-h

Table 2. Responses to questions regarding hygiene and eating behaviors of participant families, from the in-person interview of the Soil Ingestion Study.

Behavior	Child		Mother		Father	
	No.	(%)[a]	No.	(%)[a]	No.	(%)[a]
Frequency of tooth-brushing (times/day)						
<1	3	(15.8)	0	—	0	—
1–2	8	(42.1)	5	(26.3)	10	(52.6)
2 or more	8	(42.1)	14	(73.7)	9	(47.4)
Washes hands before meals						
Yes	14	(73.7)	16	(84.2)	13	(68.4)
No	5	(26.3)	3	(15.8)	6	(31.6)
Washes face before meals						
Yes	1	(5.3)	1	(5.3)	0	—
No	18	(94.7)	18	(94.7)	19	(100)
Bites or chews fingernails						
Yes	4	(21.0)	6	(31.6)	5	(26.3)
No	15	(79.0)	13	(68.4)	14	(73.7)
Contact with pet						
Yes	18	(94.7)	15	(79.0)	14	(73.7)
No	1	(5.3)	4	(21.0)	5	(26.3)
Consumes unwashed vegetables (times/week)						
From family-owned garden						
0	19	(100)	18	(94.7)	19	(100)
1	0	—	1	(5.3)	0	—
From store, neighbor's garden, etc.						
0	18	(94.7)	18	(94.7)	18	(94.7)
1	1	(5.3)	1	(5.3)	1	(5.3)
Consumes unwashed fruits or berries (times/week)						
From family yard						
0	17	(89.5)	17	(89.5)	19	(100)
1–2	1	(5.3)	1	(5.3)	0	—
>2	1	(5.3)	1	(5.3)	0	—
From store, neighbor's yard, etc.						
0	15	(79.0)	18	(94.7)	17	(89.5)
1–2	2	(10.5)	0	—	1	(5.3)
>2	2	(10.5)	1	(5.3)	1	(5.3)

[a]Percentage calculated from total number of participant families ($n = 19$).

urine collection periods were slightly more successful: 14 of 19 children and 17 of 19 mothers had no missing or incomplete urine samples for either of the two 24-h periods. Regarding fathers, 15 of 19 for the first 24-h collection, and 17 of 19 for the second 24-h collection had no missing or incomplete urine samples. Regardless of the number of incomplete 24-h urine samples, laboratory results were available for nearly all participants.

Regarding fecal samples for study days 7–13, 84% (16 of 19) of participant children provided complete fecal samples, and 16% (three of 19) of children provided fecal samples with at least one missing or incomplete collection. In total, 74% of mothers and 89% of fathers provided complete fecal samples, with the remainder providing samples with at least one missing or incomplete collection. As with the urine, chemical analyses were conducted on all samples, regardless of completeness.

During the 4 days in which the daily diary was completed for all study participants (study days 4–7), all 19 children spent at least some time outside playing around the house and yard; therefore, surface and core soil samples were collected and analyzed for all 19 children. Two of 19 each of

Table 3. Responses to questions regarding child's mouthing behavior, from the in-person interview of the Soil Ingestion Study.

Behavior	No. of children	(%)[a]
Sucks thumb or fingers		
Yes	3	(15.8)
No	16	(84.2)
Carries around a favorite blanket, toy, or stuffed animal		
Yes	11	(57.9)
No	8	(42.1)
Takes item outside		
Yes	2	(10.5)
No	9	(47.4)
Puts item in mouth		
Yes	2	(10.5)
No	9	(47.4)
Mouths furniture or licks window sills		
Yes	3	(15.8)
No	16	(84.2)
Takes food or liquid outside		
Yes	18	(94.7)
No	1	(5.3)
Swallows dirt (times/week)		
Never	8	(42.1)
1–2	6	(31.6)
3–10	4	(21.0)
>10	1	(5.3)

[a]Percentage calculated from total number of participant children ($n = 19$).

Table 4. Responses to questions regarding parents' occupational and recreational behaviors involving contact with soil, from the in-person interview of the Soil Ingestion Study.

Behavior	Mother		Father	
	No.	(%)[a]	No.	(%)[a]
Occupational contact with soil or dirt (hours/week)				
None	10	(52.6)	14	(73.7)
1–10	8	(42.1)	1	(5.3)
10–20	1	(5.3)	0	—
20 or more	0	—	4	(21.0)
Outdoor activities				
Yard work[b] (hours/week)				
None	0	—	2	(10.5)
1–5	13	(68.4)	10	(52.6)
5–10	6	(31.6)	5	(26.3)
10 or more	0	—	2	(10.5)
Recreation[c]				
None	5	(26.3)	3	(15.8)
1–5	10	(52.6)	7	(36.8)
5–10	2	(10.5)	4	(21.0)
10 or more	2	(10.5)	5	(26.3)
Indoor activities				
Housework[d]				
None	0	—	10	(52.6)
1–5	17	(89.5)	8	(42.1)
5–10	1	(5.3)	0	—
10 or more	1	(5.3)	1	(5.3)
Remodeling/indoor carpentry				
None	15	(79.0)	11	(57.9)
1–5	4	(21.0)	7	(36.8)
5 or more	0	—	1	(5.3)

[a]Percentage calculated from total number of participant families ($n = 19$).
[b]Includes gardening, weeding, mowing, trimming bushes/hedges, sweeping, and other yard maintenance.
[c]Includes sports and/or games, camping, playing, water sports, and attending outdoor auctions.
[d]Includes cleaning, sweeping/vacuuming, dusting, laundry, and caring for houseplants.

mothers and fathers did not spend any time outdoors around the house and yard; hence, no surface or core soil samples were collected for these individuals. Of the remaining 17 mothers and 17 fathers, one mother and two fathers spent time outdoors on surfaces in which core soil samples could not be obtained. Therefore, core soil samples were collected and analyzed for 16 mothers and 15 fathers. Household dust was collected and analyzed from the homes of all 19 families.

Table 6 presents the results of the chemical analyses for the food/liquid, excreta, soil, and household dust samples. Concentrations of aluminum, silicon, and titanium were generally lowest in urine samples, and considerably more concentrated in the fecal samples. Regardless of the source of the sample, silicon was present in substantially higher concentrations than either aluminum or titanium. Children consumed the least amount of food and liquid and fathers consumed the most. Aluminum concentrations in food/liquid were similar across the three family members, but silicon and titanium differed somewhat. While children's and mothers' food samples had similar concentrations of silicon, the silicon concentration of fathers' samples were considerably higher. Titanium levels in food/liquid among the three family members vary according to whether the mean or median level is considered: while children's mean titanium levels were similar to mothers and higher than fathers, children's median levels were higher than both mothers and fathers. For all family members, aluminum concentrations in urine were lower for the 5-day collection than for either 24-h period. Silicon concentrations were higher for the last 24-h period than for the other two collection periods. Titanium concentrations did not differ substantially over the three time periods and were overall quite low. Within each urine collection period, tracer concentrations were similar across all three family members. Compared to parents, children had higher concentrations of aluminum and silicon, but not titanium in feces. Mothers had the lowest silicon concentrations, but the highest titanium concentrations. Fathers had the lowest titanium concentrations.

Regarding core and surface soil samples, concentrations of the three tracer elements were nearly identical for all three

Table 5. Completeness of data collection and laboratory analyses of food and excreta, by family participant, Soil Ingestion Study.

Sample type	Sample days	Participant	Collected					
			Complete[a]		Incomplete[b]		Analyzed for tracer elements[c]	
			No.	(%[d])	No.	(%[d])	No.	(%[d])
Food/liquid	Days 6 –12	Child	19	(100)	0	—	19	(100)
		Mother	19	(100)	0	—	19	(100)
		Father	19	(100)	0	—	19	(100)
Urine	Days 7–11[e]	Child	10	(52.6)	9	(47.4)	12	(63.2)
		Mother	15	(79.0)	4	(21.0)	18	(94.7)
		Father	15	(79.0)	4	(21.0)	18	(94.7)
	Day 12: 24-hour sample	Child	14	(73.7)	5	(26.3)	19	(100)
		Mother	17	(89.5)	2	(10.5)	18	(94.7)
		Father	15	(79.0)	4	(21.0)	19	(100)
	Day 13: 24-hour sample	Child	14	(73.7)	5	(26.3)	19	(100)
		Mother	17	(89.5)	2	(10.5)	19	(100)
		Father[f]	17	(89.5)	1	(5.3)	18	(94.7)
Feces	Days 7–13	Child	16	(84.2)	3	(15.8)	19	(100)
		Mother	14	(73.7)	5	(26.3)	19	(100)
		Father	17	(89.5)	2	(10.5)	19	(100)
Surface Soil	Day 12	Child	19	(100)	0	—	19	(100)
		Mother	17	(89.5)	2	(10.5)	17	(89.5)
		Father	17	(89.5)	2	(10.5)	17	(89.5)
Core Soil	Day 12	Child	19	(100)	0	—	19	(100)
		Mother	16	(84.2)	3	(15.8)	16	(84.2)
		Father	15	(78.9)	4	(21.0)	15	(78.9)
Household Dust	Day 5	Family	19	(100)	0	—	19	(100)

[a]No missing or incomplete samples.
[b]Includes sample periods with at least one missing or incomplete sample.
[c]Aluminum, silicon, titanium.
[d]Percentage calculated from total number of participant families ($n = 19$).
[e]Urine was collected at first morning and last evening void for this 5-day period.
[f]The father of one family left town on day 13 and did not provide any samples for this day.

family members, and core and surface soil tracer concentrations were significantly correlated within each tracer element (correlation coefficients ranged from 0.38 to 0.75, $P < 0.01$). The three family members shared a common composite house dust sample (see above); however, across families, house dust concentrations of all three tracers varied approximately two-fold between the lowest and highest concentrations (aluminum: range = 2.6–5.8% wt; silicon: range = 12.3–24.8% wt; and titanium: range = 0.3–0.7% wt). House dust silicon concentration was correlated with surface soil silicon concentration (correlation coefficient = 0.32, $P = 0.02$), but not with core soil silicon concentration (correlation coefficient = 0.15, $P = 0.28$). Concentrations of aluminum and titanium in house dust were not correlated with those tracers found in core or surface soil.

Table 7 presents the results of the chemical analyses of medications taken by the study participants during data collection. Total amounts and tracer concentrations of individual medications used during the final 7 days of data collection are summarized across family members and medication type (solid or liquid). Liquid medications in particular had fairly high concentrations of tracer elements, but the amounts taken were generally quite small.

Summary statistics of estimated soil ingestion for each of the three family members is presented in Table 8. For individual study participants, ingestion estimates did not differ substantially using core or surface soil, or household dust, in the "soil" component of Eq. (1) (above). Thus, estimates are presented based on using core soil tracer concentrations of aluminum, silicon, and titanium in the ingestion calculations. Since the core soil tracer element concentrations were nearly identical for each of the three family members (see Table 6), the mean concentrations of aluminum, silicon, and titanium were calculated for each family, and these "family means" were used in ingestion calculations whenever the core soil data were missing for a given individual. Soil ingestion could not be estimated if laboratory results for food or excreta data were missing;

Table 6. Mean and median measured concentrations of tracer elements, by sample type and family participant, Soil Ingestion Study.

Sample type	Participant	N[a]	Dry weight (g/day)		Tracer element (μg/g dry weight)[b] Aluminum		Silicon		Titanium	
			Mean	Median	Mean	Median	Mean	Median	Mean	Median
Food/liquid	Child	19	285.6	287.2	27.3	18.5	50.0	39.5	23.5	9.9
	Mother	19	395.3	367.7	23.3	14.1	53.8	46.5	24.0	4.3
	Father	19	520.6	460.6	24.3	19.5	101.6	62.5	15.4	6.3
Urine										
Days 7–11	Child	12	9.2	8.9	0.76	0.63	24.8	23.6	0.62	0.55
	Mother	18	14.5	13.8	0.96	0.63	32.2	32.6	0.72	0.72
	Father	18	20.1	18.7	0.79	0.63	33.4	28.7	0.76	0.57
Day 12	Child	19	15.4	16.7	1.87	1.50	29.3	25.4	0.78	0.80
	Mother	18	31.4	31.2	2.08	1.50	25.6	24.2	0.69	0.67
	Father	19	43.5	44.6	1.85	1.50	24.9	22.5	0.75	0.75
Day 13	Child	19	17.0	17.7	1.56	1.24	72.0	51.4	0.84	0.82
	Mother	19	34.6	36.7	1.43	1.03	53.0	43.3	0.66	0.66
	Father	18	52.7	51.9	1.32	1.03	61.7	59.8	0.78	0.79
Feces	Child	19	13.4	13.6	767.5	440.0	1701.3	1450.0	516.3	279.0
	Mother	18	18.5	15.6	610.8	333.0	1272.0	1040.0	602.2	385.0
	Father	19	28.0	28.9	565.5	386.0	1537.8	1210.0	318.7	213.0
Core soil	Child	19	—[c]		6.47	6.52	27.4	27.8	0.62	0.56
	Mother	16			6.51	6.57	27.4	27.7	0.62	0.59
	Father	15			6.40	6.42	27.4	27.6	0.60	0.58
Surface soil	Child	19	—[c]		6.16	6.31	26.4	26.8	0.60	0.59
	Mother	17			6.34	6.32	27.2	27.5	0.62	0.58
	Father	17			6.26	6.22	27.2	27.1	0.59	0.56
House dust	Family	19	—[c]		4.75	4.96	20.1	20.2	0.51	0.54

[a]Number of participants with laboratory results for the given sample type.
[b]Soil and dust concentrations are presented in % weight.
[c]Soil samples were analyzed in aliquots weighing approximately 0.25 g.

therefore, soil ingestion could only be calculated for 12 of 19 children since seven children had missing urine data for days 7–11. Similarly, 16 mothers and 17 fathers had complete food and excreta data, and thus summary statistics of ingestion estimates are based on these numbers.

Within each family member grouping (children, mothers, fathers), the titanium tracer produced the highest estimates of soil ingestion. Relative to mothers and fathers, children had the lowest mean soil ingestion when estimates were based on aluminum and titanium tracers, but had the highest mean ingestion using silicon as the tracer element of interest. Using Spearman Rank correlation coefficients, within-family correlations of soil ingestion were investigated, and no clear pattern emerged. Regardless of the tracer element used, children's soil ingestion does not appear to be associated with either their mothers' or their fathers' ingestion, nor do mothers' and fathers' soil ingestion appear to be correlated. Mothers' and fathers' ingestion estimates were nonsignificantly positively correlated using aluminum and silicon tracers (correlation coefficient = 0.45, $P = 0.09$; and 0.24, $P = 0.39$, respectively), but negatively correlated using titanium tracer (correlation coefficient = -0.11, $P = 0.70$). Children's and parents' ingestion estimates were negatively correlated using aluminum tracer (correlation coefficient = -0.27, $P = 0.39$), but positively correlated using silicon and titanium (correlation coefficients = 0.14, $P = 0.66$; and 0.28, $P = 0.37$, respectively).

Estimated soil ingestion was investigated according to responses from selected behaviors reported in the in-person interview that potentially could be related to soil ingestion and which had sufficient numbers in behavior categories for investigation. Among both parents and children, neither eating unwashed fruits or vegetables (from any source), nor nail biting was associated with increased soil ingestion. However, washing hands before meals was associated with increased soil ingestion, contrary to the expectation that hand-washing would decrease soil ingestion. Among children, thumb-sucking, carrying around a blanket or toy, or

Table 7. Average daily quantity and tracer concentrations of medications used in the Soil Ingestion Study, by medication type (solid or liquid) and family participant.

Medication type	Participant	N[a]	Average daily quantity[b]	Tracer element[c]					
				Aluminum		Silicon		Titanium	
				Mean	Median	Mean	Median	Mean	Median
Solid	Child	8	0.71	1231.1	866.4	3506.6	2996.4	3.82	0.96
	Mother	16	0.49	6781.8	405.8	10633.1	2935.9	2880.6	2884.9
	Father	11	0.79	398.9	432.0	3841.0	2421.2	618.6	2.74
Liquid	Child	2	9.2	0.30	0.30	13.4	13.4	0.07	0.07
	Mother	6	6.8	237.1	0.60	836.9	4.3	0.06	0.03
	Father	5	12.4	42.2	0.30	44.2	3.8	0.28	0.02

[a]Number of participants who used the given medication type during the final 7 days of data collection.
[b]Solids: g/day; liquids: ml/day.
[c]Medication tracer concentrations are presented in μg/g dry weight for solids and μg/ml for liquids.

Table 8. Mean values of estimates of soil ingestion (mg/day) based on aluminum, silicon, or titanium tracer and core soil sample, by family participant, Soil Ingestion Study.

Participant	Tracer element	Estimated soil ingestion[a] (mg/day)			
		Mean	Median	Std	Maximum
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	1394.3
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	2899.1

[a]For some study participants, estimation of 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.

furniture licking was not associated with increased soil ingestion (data not shown) However, children's reported eating of dirt was associated with increased estimated soil ingestion using aluminum or silicon, but not titanium (aluminum: 51.2 *versus* 16.5 mg/day, silicon: 45.0 *versus* 28.5 mg/day, titanium: 129.0 *versus* 315.8 mg/day, ever *versus* never eat dirt). Among parents, doing indoor carpentry, outside yard work, or participating in outdoor recreational activities was not associated with increased estimated soil ingestion (data not shown). However, fathers' occupational contact with soil was associated with an increase in soil ingestion, particularly when the aluminum and titanium tracers are considered (aluminum: 136.8 *versus* 39.9 mg/day, silicon: 29.2 *versus* 24.8 mg/day, titanium: 929.7 *versus* 497.9 mg/day, any hours/week *versus* no hours/week). Similar results were observed for mothers using aluminum and titanium tracers, but not silicon (aluminum: 146.6 *versus* 37.6, silicon 22.7 *versus* 24.7, titanium: 503.2 *versus* 214.8, any hours/week *versus* no hours/week).

Soil ingestion could not be calculated for a number of participants due to missing urine data (seven children, two mothers, and two fathers). As tracer concentrations in urine were quite low and therefore have limited impact on soil ingestion estimates, alternate estimates were calculated disregarding the urine component of Eq. (1), and the analyses described above were repeated. As expected, ingestion estimates were slightly reduced among those participants with complete data, since the total estimated amount of tracer excreted is reduced when tracer in urine is ignored. Overall, mean and median ingestion estimates did not change appreciably with the addition of the participants with missing urine data (e.g., children's mean soil ingestion was 33.2 mg/day, 27.8 mg/day, and 313.8 mg/day for aluminum, silicon, and titanium tracers, respectively). Furthermore, the relationships between soil ingestion and the selected behaviors described above did not change.

Discussion

This study was designed to meet several objectives, including estimation of soil ingestion during normal activities in children and their parents, identification of behavioral and lifestyle factors potentially related to soil ingestion values, comparison of adult and child soil ingestion estimates within the same family, and investigation of gender differences in soil ingestion by comparing estimates between the male and female parent of the same family. The estimates of soil ingestion for children in the present study are within the ranges of estimates reported by previous studies (Binder et al., 1986; Clausing et al., 1987; Calabrese et al., 1989; van Wijnen et al., 1990; Stanek and Calabrese, 1995), and fall within current federal guidelines which suggest the use of a mean of 100 mg/day and upper confidence limit of 400 mg/day (USEPA, 1996). Furthermore, these estimates are within the range of those reported in the previous study of 104 children conducted by the investigative team (Davis et al., 1990), of which these children were a subset. It should be noted that the children in this study are somewhat older than those in previous studies, which could result in lower soil ingestion rates possibly due to decreased mouthing behavior that might be expected with increasing age. With respect to the aluminum and silicon tracers, soil ingestion estimates for adults are in agreement with those from two smaller studies of adult soil ingestion (Calabrese et al., 1990; Stanek et al., 1997), as well as current federal guidelines which suggest a mean of 50 mg/day (USEPA, 1996). No federal guidelines have been set for an upper confidence limit of daily soil ingestion in adults, due to the paucity of data in this area. Interestingly, mothers' and fathers' mean estimated soil ingestion was higher than the children's, contrary to what might be expected. However, median estimates are higher for children than adults for aluminum and silicon, indicating that adult estimates are somewhat skewed towards lower values. Regardless of the tracer element used in the estimation, estimated soil ingestion in the adults was considerably more variable than for the children, possibly indicating an important occupational contribution of soil ingestion in some, but not all, of the adults.

Similar to previous studies, the highest ingestion estimates resulted from using titanium as the tracer element of interest. Toothpaste is a known source of titanium dioxide, and may represent an important non-food, non-soil source of this element. In the present study, every participant was provided with a tube of toothpaste and instructed to use only this toothpaste throughout the study period, and parents were asked to monitor their child while brushing to minimize the amount of toothpaste ingested. However, the titanium concentration of the toothpaste provided is unknown, making it difficult to determine whether the higher observed soil ingestion estimates using titanium are the result of toothpaste ingestion. A number of behaviors suspected to be related to soil ingestion were investigated, and only two were found to be associated with increased ingestion: among children, reported eating of dirt was associated with the amount of soil ingested, and for adults, occupational contact with soil was associated with increased ingestion. In this study, typical childhood behaviors thought to contribute to soil ingestion, including thumb-sucking, furniture licking, or carrying around a blanket or toy were not associated with increased soil ingestion in the participant children. It should be noted, however, that thumb-sucking and mouthing furniture were each reported for only three of 19 children, and the number was further reduced to two of 12 children for thumb-sucking, and one of 12 children for furniture-mouthing when results were restricted to those with complete data for estimating soil ingestion. A behavior that one could reasonably assume to be associated with soil ingestion, eating unwashed fruits or vegetables, was not associated with soil ingestion in either children or adults. However, the study design required an equal amount of any food consumed, including fruits and vegetables, to be included in the food sample for analysis. Thus, assuming that the duplicate fruit or vegetable sample was also unwashed, and since the amount of a given tracer element in food is subtracted from the amount of tracer in excreta in the "mass balance" approach to estimate soil ingestion (see Eq. (1)), consuming unwashed fruits or vegetables would not have contributed to an increase in estimated soil ingestion. Washing hands before meals was associated with increased soil ingestion, although these results are based on relatively few participants who do not wash their hands before eating and for whom soil ingestion could be estimated (two of 12 children, three of 16 mothers, and five of 17 fathers). It was initially thought that hand-washing prior to meals would decrease soil ingestion, but it is possible that those individuals who wash hands prior to meals engage in activities involving contact with dirt (presumably resulting in higher soil ingestion), necessitating hand-washing before eating.

This study found that, within a given family, children's soil ingestion does not appear to be associated with either parent's ingestion, nor do mother's and father's soil ingestion appear to be correlated. At the time of fieldwork, this was the first study to investigate soil ingestion in both children and adults, and at present, is the first such study to investigate soil ingestion within a family. Given the relatively small number of families for which within-family comparisons could be made (10 families had complete ingestion data for all three family members), it is difficult to conclude definitively whether estimates of soil ingestion among family members are independent from one another, or whether behaviors shared among family members and also suspected to be associated with soil ingestion make no contribution towards estimates of ingestion within a family.

The "mass-balance" approach to estimate soil ingestion relies on several underlying assumptions. First, it is assumed that the tracer element used in the calculation is not well-absorbed from the gastrointestinal tract, so that any tracer consumed in food/liquid or medicines readily passes through the digestive system and is excreted in the feces, but not urine, of an individual (urinary excretion of a tracer indicates absorption by the digestive tract). Thus, any remaining amount of tracer is assumed to come from the ingestion of soil. Further, an ideal tracer element should be present in considerably greater concentrations in soil than in food/liquid or medicines, in order to increase the likelihood that any ingested tracer does indeed come from soil. In the present study, the food/liquid samples had measurable amounts of all three tracers of interest. Furthermore, some soil ingestion estimates had negative values for some of the participants, suggesting that some tracer may be absorbed in the gastrointestinal tract. However, urinary concentrations of the tracer elements (aluminum and titanium in particular) were overall quite low, indicating that relatively little tracer was absorbed in the digestive tract, and ingestion estimates were similar when urine data were ignored in the calculation. A second assumption is that children and parents ingest soil and dust primarily from their own houses and yards, and that the soil and house dust samples are representative of the entire house and yard. Since sample collection occurred during the summer months and participant children were not in school, this may be a reasonable assumption for the children. However, given that all but one of the fathers and six of 19 mothers were employed outside the home, it seems somewhat unlikely that the primary source of dust and soil for these individuals would be around the house and yard, and that any dust or soil ingested away from home would be negligible. Soil samples were not collected beyond the house and yard (i.e., no sample collection occurred at participants' work places). It should be noted, however, that the range of soil tracer element concentrations across families was quite narrow, indicating that the soil composition around the area is relatively uniform.

This was not the case for house dust: concentrations of aluminum, silicon, and titanium varied widely across homes. Although estimated soil ingestion did not differ significantly for individuals when the primary source of ingested soil was assumed to be house dust, slightly higher ingestion estimates will result when house dust concentrations are used in the $E_{\text{soil/dust}}$ component of Eq. (1) (above), due to the overall lower tracer concentrations relative to core and surface soil. At the extreme, assuming 100% of the source of ingested soil is house dust, ingestion estimates increased on average 24, 28, and 14% for children using aluminum, silicon, and titanium tracers, respectively. However, as discussed above, data collection took place during the summer months, and it is unlikely that children's sole source of ingested soil came from the indoors. Rather, it is more likely that actual ingestion estimates fall somewhere between those for core (or surface) soil and household dust.

For some participants, estimated soil ingestion was a negative value. A negative value will result when the amount of tracer present in food and medicines exceeds the tracer amount present in urine and fecal matter for a given individual. There are several possible explanations for such a result. The results of the chemical analyses of tracers in each sample are subject to a certain amount of error; given that the dried food/liquid samples were many times heavier than either the urine or fecal matter (Table 6), any overestimation of tracer amount in the food samples could not be compensated for by a similar overestimation in the tracer amounts found in urine and feces. A second possibility, noted above, is that some tracer is absorbed by the body, so that the amount consumed in food/liquid or medicines is, in fact, greater than the amount excreted in feces. Indeed, the results of a number of studies indicate that aluminum, silicon, and titanium can be absorbed in small amounts from the digestive tract in adults (Schroeder et al., 1963; Tipton et al., 1966; Schroeder, 1973; Carlisle 1974; Sorenson et al., 1974; Bowen 1979; Kelsay et al., 1979; Greger and Baier, 1983), and absorption of tracer elements may be significantly greater in children than adults, based on studies of lead metabolism (NRC, 1980). Furthermore, the results presented here indicate that at least some small fraction of tracer was absorbed in the digestive tract, as evidenced by the presence of tracers in the urine (silicon, in particular). A third possibility is that the assumption of a 24-h lag time between consumption of a tracer element in food and its subsequent excretion is not entirely correct (i.e., gastrointestinal transit time may be greater or less than 24 h for a given individual), resulting in a misalignment between the "input" and "output" components of Eq. (1). Lastly, a negative soil ingestion estimate could occur if the adjustment factors for missing urine and fecal samples are inappropriately applied. Every study participant provided complete food/liquid samples; however, there were a number of incomplete urine and fecal samples and, as described above, an adjustment factor was calculated that inflated the actual dry weight of the urine or fecal sample in proportion to the number of samples missed. If the missed sample was heavier than the collected samples, this adjustment would underestimate total sample weight which, in turn, would underestimate the total amount of tracer output in the urine and feces and potentially result in a negative estimate for soil ingestion.

In conclusion, this study found increased soil ingestion associated with reported eating of dirt in children and occupational exposure in adults. Although a number of samples were not available for laboratory analyses and limited the number of participants (children in particular) for which soil ingestion could be estimated, it remains the largest study conducted to date on soil ingestion in adults and is the first to examine soil ingestion within a family. The participant families were chosen from a subset of those in a previous study of soil ingestion due to their high compliance with the study protocol and, therefore, they may not be representative of the general population. However, they were chosen for their high compliance in order to maximize the quality of data obtained from what is undoubtedly a difficult protocol to follow. The success of the fieldwork demonstrates the feasibility of conducting studies with complex data collection methods, necessary for obtaining reliable soil ingestion estimates in free-living individuals.

As such, the ingestion estimates presented here could aid in refining current federal guidelines for soil ingestion in adults, and add further support for current estimation guidelines in children.

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