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WHY ON EARTH?: EVALUATING HYPOTHESES ABOUT THE PHYSIOLOGICAL FUNCTIONS OF HUMAN GEOPHAGY

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ABSTRACT

Geophagy has been hypothesized to be an adaptive behavior, either as a means to allay nutrient deficiency or to protect against ingested pathogens and toxins. Others have proposed that geophagy is non-adaptive, occurring either to allay hunger or as an epiphenomenon of nutrient deficiencies. This paper evaluates these hypotheses using 482 published cultural-level accounts of human geophagy and 330 accounts of geophagy among 297 species of mammals, birds, and reptiles. Information was extracted from reports of human geophagy to permit statistical analysis; reports of non-human geophagy were tabulated. Human geophagy did not parallel changes in nutrient requirements, occurred most frequently among children and pregnant women and in tropical areas (where pathogen densities are highest), and was associated with ingestion of toxic substances and gastrointestinal distress. Earth ingested by humans was craved and carefully selected and prepared; it had high clay

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content, but few bioavailable mineral nutrients. In primates, geophagy was associated with both protection from toxins and obtaining nutrients, whereas in other vertebrates it was associated mainly with obtaining nutrients. Our results indicate that human geophagy is best explained as providing protection from dietary chemicals, parasites, and pathogens, whereas animal geophagy may involve both micronutrient acquisition and protection.

Introduction

GEOPHAGY IS the intentional consumption of earth. It is a specific type of the more general phenomenon that is commonly referred to as "pica," the purposive consumption of non-food substances. Geophagy is widely practiced: it has been observed in hundreds of cultures on all inhabited continents (Laufer 1930; Anell and Lagercrantz 1958). Geophagy was first documented by Hippocrates (460–380 BC) more than 2000 years ago (Hippocrates and Adams 1849). However, archeological evidence suggests that the practice of geophagy is thousands of years older and may date back to *Homo habilis* (Baudouin 1924; Clark 2001; Brady and Rissolo 2006). Earth eating continues throughout the world today (Young 2010, 2011).

Scholars from diverse fields including anthropology, behavioral ecology, biochemistry, ethology, geography, and medicine have offered a range of hypotheses for why earth is consumed. Yet, even after much investigation, geophagy remains an enigma for many reasons (Young 2010). These include the scarcity of hypothesis-driven research as well as the typically single-discipline approaches to its study. It is also due to underreporting, firstly because researchers often do not inquire about geophagy and, secondly, even if they do, fear of being judged harshly leads some geophagists to conceal their behavior (Young et al. 2008).

Because of both the prevalence of geophagy and its association with positive and negative health consequences, there is a clearly acknowledged need to understand the etiology of the behavior. Indeed, calls for elucidation of the physiological functions of this fascinating and enigmatic phenomenon are a recurring theme in the geophagy literature (e.g., Whiting 1947; Edwards et al. 1994; Geissler et al. 1997; Limpitlaw 2010).

The Hypotheses

Three general physiological explanations for the etiology of human geophagy have been advanced. The first two suggest contexts in which the behavior would be adaptive, whereas the third suggests that it is not an adaptive behavior.

Hypothesis 1: Nutrient Deficiency. This hypothesis proposes that people eat earth in order to make up for dietary deficiencies of mineral micronutrients, particularly iron and zinc (Hunter 1973; Çavdar et al. 1983; Prasad 2001b) and the macromineral calcium (Wiley and Katz 1998). For brevity, these will collectively be referred to as nutrients. Because anemia (the state of insufficient red blood cells or hemoglobin) is frequently associated with geophagy (Geissler et al. 1999; Kawai et al. 2009), the most commonly reiterated of the nutrient hypotheses suggests that geophagy remedies iron deficiency. It should be noted, however, that anemia can be caused by micronutrient deficiencies other than iron, as well as infections and blood loss (Yip and Dallman 1988). Sodium deficiency has been proposed to motivate geophagy in non-human primates and other animals (Jones and Hanson 1985; Krishnamani and Mahaney 2000). However, human geophagists do not attribute their behavior to a dearth of salt (Vermeer and Frate 1979; Kraemer 2002) and with only a few exceptions (Laufer 1930), geophagic earth is not typically salty (Young et al. 2008).

Hypothesis 2: Protection. This hypothesis proposes that earth is eaten as a medicament, to reduce the short-term malaise and long-term effects of harmful chemicals and parasites and pathogens. Many human food plants produce toxic chemicals, such as tannins and glycoalkaloids to protect themselves from biotic enemies (pathogens and herbivores). Other sources of harmful chemicals in the human diet are enterotoxins secreted by food- and waterborne bacteria such as *Escherichia coli, Staphylococcus aureus, Salmonella enterica*, and *Listeria monocytogenes.* Ingestion of these toxins can cause gastrointestinal distress, dizziness, and muscle pains; in sufficient quantities, they can be mutagenic, carcinogenic, or deadly (Hui et al. 2001b). Dangerous pathogens include food- and waterborne bacteria as well as viruses and parasitic nematodes.

Under this hypothesis, there are two mechanisms by which geophagic earth may be protective: by *reducing the permeability* of the gut wall to toxins and pathogens and by *binding directly* to toxins and pathogens (Young 2010). The intestinal mucosal layer acts as a physical barrier between ingesta and the bloodstream by filtering out large molecules, as well as a chemical barrier by maintaining a pH gradient. Geophagic earth, especially if it is clay-rich, can bind with and thereby reinforce the protective mucosal layer and/or enhance mucosal secretion, thereby reducing permeability of the intestinal walls (González et al. 2004).

The second mechanism involves binding directly to toxins, parasites, and other pathogens. This can either render them unabsorbable by the gut or inhibit their respiration. Hladik and Gueguen (1974) first proposed that clays were protective against plant secondary compounds consumed by primates, and Profet (1992) suggested that clays could be protective against human teratogens. A number of clays found in geophagic earths are capable of binding pathogens, including viruses (Lipson and Stotzky 1983; Rey 1989; Dornai et al. 1993), fungi (Smith and Carson 1984; Lavie and Stotzky 1986a,b; Phillips et al. 2008), and bacteria (Maigetter and Pfister 1975; Said et al. 1980; Ditter et al. 1983; Gardiner et al. 1993), as well as toxins, including poisonous herbicides (Okonek et al. 1982; Lotan et al. 1983), pharmaceuticals (Tsakala et al. 1990), and plant secondary compounds (Johns 1986; Johns and Duquette 1991; Gilardi et al. 1999; Houston et al. 2001; Dominy et al. 2004). It is also possible that earth inhibits larger pathogens (e.g., geohelminths) from colonizing hosts (Krishnamani and Mahaney 2000) although the mechanism by which this occurs has not been elucidated.

Hypothesis 3: Non-Adaptive. This hypothesis proposes that there is no benefit to eating earth. Instead, people do so either because they have no food to eat or because micronutrient deficiencies have caused neurological or sensory problems. In the first case, earth is supposedly consumed to ease hunger pains when no other food is available (e.g., La Billardière 1800; Mallory 1926; Wiley and Katz 1998). In the second case, cravings for earth are suggested to be epiphenomena of nutrient deficiencies that affect appetite-regulating brain enzymes (von Bonsdorff 1977; Youdim and Iancu 1977) or taste sensitivity (Chisholm and Martin 1981; Prasad 2001a), causing non-food substances to become appealing.

AIMS

This paper has two aims. First, we provide an updated review of the literature on geophagy in humans and, for comparison, in other vertebrates. For the human literature, our starting points were eight excellent monographs and reviews (Laufer 1930; Anell and Lagercrantz 1958; Hochstein 1968; Danford 1982; Sayetta 1986; Loveland et al. 1989; Horner et al. 1991; Reid 1992) which were then augmented by primary sources. We compiled this information into a database that enabled us to quantitatively describe geophagy worldwide and investigate the circumstances under which it occurs. Our second aim was to use the database on human geophagy to systematically evaluate the three hypotheses for the etiology of geophagy. This paper does not directly address the cultural forces and beliefs that shape geophagy (the proximate determiners of the behavior), but rather explores the ecological triggers and physiological underpinnings of geophagy (the ultimate causes). Socioeconomic status may be an underlying cause of hunger, nutrient deficiency, or increased exposure to toxins and pathogens, but it is not a direct cause of geophagy itself. Therefore, it is not an alternative explanation for geophagy and is not tested here.

Additionally, we synthesized reports of geophagy by non-human animals to provide further insights into the distribution of the behavior and its potential physiological causes. Our starting points were several excellent reviews of geophagy in animals (Jones and Hanson 1985; Kreulen 1985; Krishnamani and Mahaney 2000; Ferrari et al. 2008). Because this information was far less detailed and comprehensive than data on humans, it was tabulated, but not analyzed statistically.

METHODOLOGY

LITERATURE SEARCHING

Initially, we searched online databases (Agricola, Dissertation Abstracts, Google Scholar, Human Relation Area Files, ISI Web of Science, JSTOR, Library of Congress, LexisNexis, OCLC, Proquest Historical Newspapers, PubMed, and Zoological Record) for entries containing "geophagy," "geophagia," "pica," "clay eating," "chalk eating," "cachexia Africana," "mal d'estomac," "malacia," "citta," "erde essen," "aarde eten," and "dirt eating." We sought information on geophagy in humans, non-human primates, and other vertebrates. We used the reference lists in each identified publication to locate additional primary sources. This process was iterated until no new references were found. Our search was not restricted by language, format of reference (e.g., microfiche and thesis, among others), or date of publication; the references span many languages and nearly 500 years.

CRITERIA AND RATIONALE FOR INCLUSION

We defined geophagy as the regular, purposive consumption of earth. With this definition, the mouthing behavior of young children is excluded (their earth consumption may not be intentional, but rather part of a larger behavior of environmental exploration). Instances of geophagy that were described as purely symbolic, such as the ingestion of tiny amounts during solemn occasions (oaths, mourning, tests of innocence or for religious purposes) also were excluded. Finally, if a mineral found in soil was used in the preparation of food, but was not ultimately consumed, such as during nixtamalizaton (the soaking of corn in a limestone solution before grinding), it was not considered geophagy.

The human geophagy literature can be classified into five categories: 1) individual case reports—e.g., a Turkish woman living in Paris ate chalk and clay every day (Henon et al. 1975); 2) an enumerated population—e.g., 55% of anemic Namibian women eat earth (Thomson 1997); 3) a cultural group—e.g., pregnant Otomacs regularly engage in clay-eating (von Humboldt et al. 1821); 4) soil analysis studies—e.g., montmorillonite was a major component of *ch'aqu* (Browman and Gunderson 1993:415); and 5) literature reviews in which no new data were presented—e.g., "According to La Billardière and confirmed by the reports of Hekmeyer [clay] figures are crunched on by women and children" (Ferrand 1886: 549).

In constructing our database on human geophagy, we focused on firsthand reports of geophagy among cultural groups (category 3). If an author referred to a report of geophagy by someone else (category 5), we obtained the original document. This insured that reports were not included more than once, and that the translation was of high quality. Thus, the unit of analysis for our study is a "cultural report." We did not include reports of individual cases of geophagy (category 1) because of the likelihood of bias regarding both health consequences (people not suffering ill health are unlikely to visit a health care provider) and geographical occurrence (health care providers are not equally available worldwide). We also did not include studies of groups among whom geophagy was studied because of a biological or behavioral condition (e.g., anemia, dialysis, lead poisoning; category 2) because they were not representative of the population at large. Results from soil analyses (category 4) are drawn on throughout the paper.

In reviewing the animal literature, we focused on geophagy and excluded lithophagy (ingesting of rocks or grit). Authors referred to animal geophagy using the terms "clay

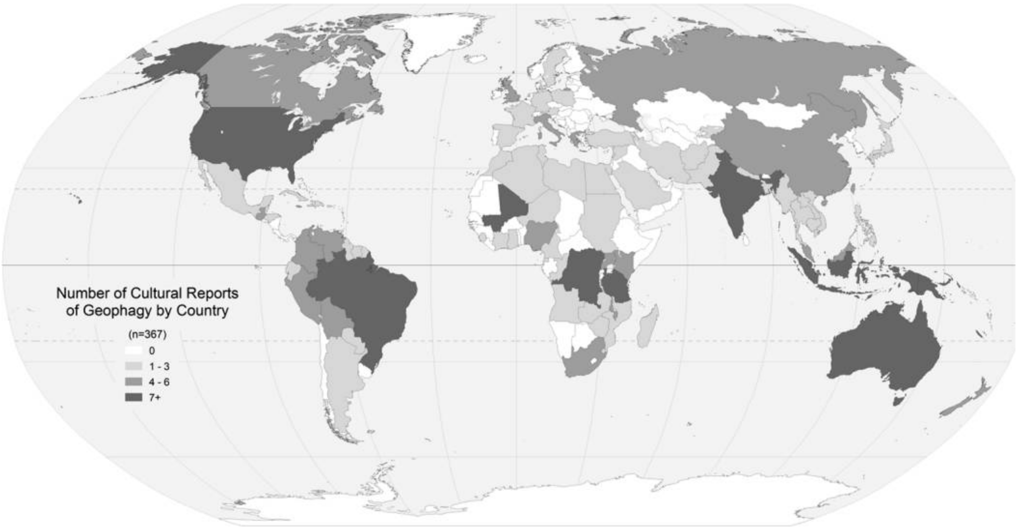


Figure 1. Worldwide Distribution of Cultural Reports of Geophagy

licks," "mineral licks," "salt licks," and "geophagy"; all such descriptions were included in our tables and analysis. The original document was obtained whenever possible; reports citing personal communication were not included. We located 330 ethological accounts of geophagy among mammals, birds, and reptiles encompassing 297 species and 26 orders.

CONSTRUCTING THE DATABASE ON HUMAN GEOPHAGY

From each article on human geophagy we extracted information on as many of the following variables as possible: year of observation, geographic location, climate, non-food materials consumed (e.g., appearance, source, preparation), life stage of the consumer (e.g., child, adolescent, pregnant), and any associations with physiological conditions, such as gastrointestinal distress, anemia, and hunger. If several reports were made about earth eaten by the same group of people or in the same area within a 10-year span, but by different authors, these were combined into one cultural report. A custom built Web-based form was developed specifically for this project using Ruby on Rails software (http://www.rubyonrails.org/), and information from each article was entered manually. Data from biological, epidemiological, and cultural sources were included, making a biocultural analysis possible.

Our database on human geophagy included 482 publications, which contained 367 separate cultural reports of geophagy from all over the world (in supplementary material, available at *The Quarterly Review of Biology* homepage, http://journals.uchicago.edu/QRB). This database includes every obtainable, written culture-level report of human geophagy. To our knowledge, it is the most complete compilation of such information in existence. References for all sources are listed in the supplementary materials; the entire "Pica Literature Database" will be made available once all planned analyses have been completed.

Constructing a map of the frequency of occurrence of geophagy worldwide (Figure 1) presented a challenge because observations at the level of the cultural group do not "map" perfectly onto political maps, since cultures sometimes are dispersed over several countries or located in just one section of a country. To achieve a reasonable approximation, we selected the country in which the ethnic group was primarily situated at the historical time described in the original paper(s).

We used Köppen's classification system to categorize the climatic regions in which geophagy occurs (Kottek et al. 2006). The Köppen system separates climates into five categories: polar, cold, temperate, tropical, and dry (McKnight and Hess 2005). To test whether the distribution of geophagy by climate type was different from the distribution of cultural reports by climate type, we classified each of the 186 cultures in the Standard Cross-Cultural Sample (SCCS) (Murdock and White 1969) by climate type. Cultures in the SCCS were chosen because of their independence from each other, so use of the SCCS minimizes "Galton's problem" of lack of independence of cultures in close geographical proximity to each other (Naroll 1961). Additionally, we compared the geophagy distribution to the world population distribution by climate region (Staszewski 1963).

Because information on human geophagy spans 2000 years and includes reports from many fields of study, the quality and detail of observations varies widely. Accounts were written by ethnographers, colonial explorers, government officials, missionaries, medical doctors, nurses, nutritionists, and journalists. Some reports of geophagy are lengthy (e.g., more than 20 pages), and describe in detail the characteristics of individuals who practice geophagy, when in their lifetimes they do so, sources and preparation of earth, and costs, among other topics, whereas other reports are no more than brief mentions (e.g., a single phrase in a 417-page ethnographic report).

The literature on non-human geophagy was far less detailed and specific, e.g., there were few descriptions of life stage, sex, or reproductive status of geophagists, nor the composition of earths consumed. The creation of an analyzable database of these reports could not yield similar insights, so we tabulated the ethological reports. Reports on geophagy in non-human primates were typically more detailed than those on geophagy in other vertebrates (see supplementary material, Tables 2 and 3). A "report" was defined as a description of geophagy by a particular species in one geographic location, i.e., if there were multiple observations of the same species in the same location, they were not tallied twice.

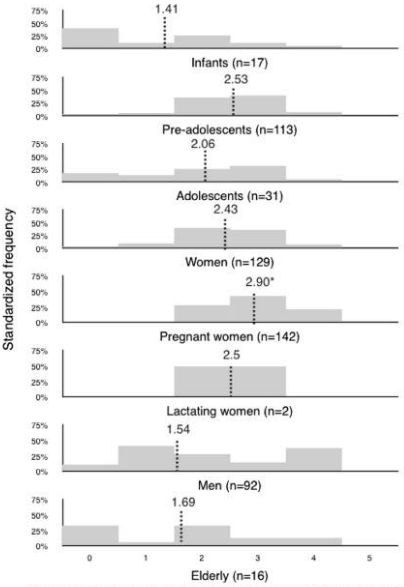
TABLE 1
Geophagy scoring system used in the operationalization of geophagy frequency

Score	Terms Associated
0	Never
1	Rarely, few
2	Sometimes, occasionally
3	Frequently, common, habit, very common, quite general, many, endemic, widely, often
4	Usually, typically
5	Always

OPERATIONALIZATION

To create variables in the database that could be analyzed, we first grouped the life stages of geophagists into eight categories: (1) "infants" are children younger than two years or are still breastfeeding; (2) "preadolescents" are children who have not reached puberty (3–12 years old); (3) "adolescents" are boys and girls who have reached puberty (13–18 years old); (4) "pregnant women" are adolescent or adult women who are gestating; (5) "lactating women" are those who are breastfeeding; (6) "women" are adults whose pregnancy or lactation status is unknown; (7) "men" are adult males; and (8) "elderly" are those described in reports as being "old" or no longer bearing children. Regarding category 6, if women's reproductive status was not mentioned, we inferred that they were not pregnant or lactating, although this may have resulted in some misclassification because in many traditional societies, women of reproductive age typically were pregnant or lactating most of the time.

Data on proportions of populations or subpopulations that engaged in geophagy were rarely given in the reports we compiled. Rather, qualitative terms such as "some," "all," "frequently," and "rarely" were used instead. In an attempt to quantify these descriptive terms, we constructed a scoring system (Table 1) similar to that of Wiley and Katz (1998).



*Compared to pregnant women, all groups have significantly lower mean geophagy scores ($p<0.0001$).

Figure 2. Standardized Geophagy Frequencies and Mean Geophagy Score (Dotted Line) by Life Stage Based on Culture-Level Reports of Geophagy

Only rarely did observers identify which subgroups within the population did not eat earth. More typically the observer would comment only on positive occurrences (e.g., "pregnant women and children eat clay"). Therefore, we standardized the frequencies by the absolute number of cultural reports made for each life stage. To do this, we divided the frequency of geophagy for each life stage by the number of cultural reports presenting information on that particular life stage (Figure 2). To reduce the geophagy frequency to a more intuitive value, we created a geophagy score, which is the mean geophagy frequency for that life stage.

When observers discussed the timing of consumption during pregnancy, terms such as "early" and "late" were used more frequently than specific months or trimesters. We classified pregnancy timing described as "early" as first trimester and grouped those described as "mid" or "late" pregnancy into a single category "second or third trimester."

"Anemia" was not a term that was in use for most of the time period encompassed by our literature review, and biomedical tests of anemia have become standard only relatively recently. Thus, associations between geophagy and mild anemia would rarely have been reported. However, we were able to identify associations with severe anemia when certain symptoms were described, e.g., pallor of skin and/or mucosal membranes and thin "watery" blood. "Chlorosis" is a term that was frequently used in the past to describe weak, pale patients; it is now considered to be synonymous with anemia (Hudson 1977). Thus, if geophagists were described as pale, having thin blood or exhibiting chlorosis, we recorded geophagy as being associated with anemia in that report.

Textures and consistencies of earths vary widely due to different proportions of the four major solid components: sand, silt, clay, and organic matter. Proportions of these components is important because each has very different effects on the body (Wilson 2003). In particular, sand is the least reactive inorganic fraction of earth, whereas clay is the most reactive (Saether and Caritat 1997). We classified geophagic earths based on qualitative descriptions in the original reports. Earth was categorized as "claylike" if the author of the report described it in terms such as "clayey," "plastic," "moldable," "used for pottery," or as "marl."

Our database includes reports of consumption of 402 different types of earth, ranging in color from bright white to light yellow, orange, red, red-brown, purple, dark grey, black, blue, and light green. If more than one type was reported to be consumed in a culture, we used only the one that was most frequently consumed for each life stage. We chose this approach because counting more than one geophagic earth would lead to oversampling if one group ate seven types of clay, each one infrequently, whereas another group ate only one type of clay, but did so frequently. For example, if a report stated that "pregnant women rarely ate red clay but usually ate grey clay," pregnant women were classified as "usually" consumers of "grey clay."

The elemental constituents of only a few geophagic earths have been chemically an-

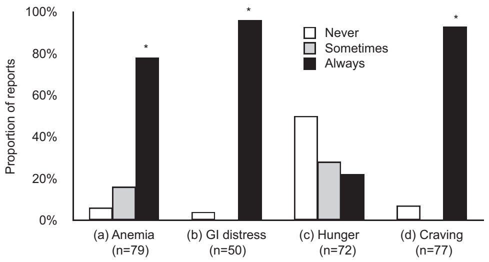


Figure 3. Reports of the Frequency of Association of Geophagy with (A) Anemia, (B) Gi Distress, (C) Hunger, and (D) Craving

The proportion of reports associated with anemia, GI distress, and craving was significantly higher (*) than expected under the null hypothesis ($p<0.005$).

alyzed; in many cases only qualitative descriptions are available. In general, it is not possible to determine the nutrient constituents of earth by visual inspection, with one exception: it can be inferred that soils contain iron if they are red in color (Jeff Wilson, personal communication). However, iron may be present if the soils are not red, because some iron-rich components result in pigmentation other than red. The calcium or zinc contents of most geophagic earths were not quantified. Even if they had been, the total elemental composition of the earth does not indicate the bioavailability of its constituents, i.e., the proportion freely available to cross an organism's cellular membranes. Bioavailability is typically much lower than total amounts (Wilson 2003).

Statistical Analyses

All statistical analyses were performed using STATA 9.2 for Macintosh (STATA Corporation, College Station, Texas). Differences in geophagy scores among sex and life-stage categories were tested using a multilevel, mixed-effect model (to control for repeated measures within a cultural report; Figure 2). Differences between observed frequency of geophagy by circumstances of consumption and the null hypothesis were tested by using Pearson's chi-square analyses (see Figures 3 and 7). We tested whether nutrient requirements could predict geophagy scores (Figure 4) using Spearman's test of non-parametric correlation.

Evaluating the Hypotheses

ADAPTIVE HYPOTHESIS 1: NUTRIENT DEFICIENCY

Association with Nutrient Deficiencies

If geophagy were a response to a nutrient deficiency, it should occur in conjunction with such a deficiency. Indeed, an association between geophagy and anemia was recognized as early as 40 AD when Cornelius Celsus, a Roman physician, wrote "those that have a bad color for a long time without jaundice, are either distrest with pains in the head, or labor under a *malacia*" (the term then used for cravings of non-food substances) (Celsus and Grieve 1756:59). The geophagy-anemia association has been confirmed repeatedly worldwide since then. For example, in Zanzibar, the Swahili term for anemia, *safura*, was mistranslated by Livingstone as "the disease of . . . earth eating" (Livingstone and Waller 1875:346). In 20th-century India (e.g., Hooper and Mann 1906) and on slave plantations in the Americas (e.g., Buckingham 1842), pallor was often used as a symptom of the disease of earth eating. Indeed, in our database, anemia and geophagy were associated significantly more often than would be expected under the null hypothesis ($p<0.001$) (Figure 3a). Available data did not permit us to test an association between geophagy and calcium or zinc deficiencies.

Frequency of Geophagy and Nutrient Requirements

If geophagy were a response to a deficiency in iron, zinc, or calcium, then we would expect people with the greatest needs to practice geophagy most often. To evaluate this corollary, we determined the daily reference intakes for each of these elements by people in each life stage (Institute of Medicine 2002; Figure 4). These values were standardized by dividing by energy requirements at each life stage to capture the relative requirements, a standard consideration in evaluating risk of nutrient deficiency.

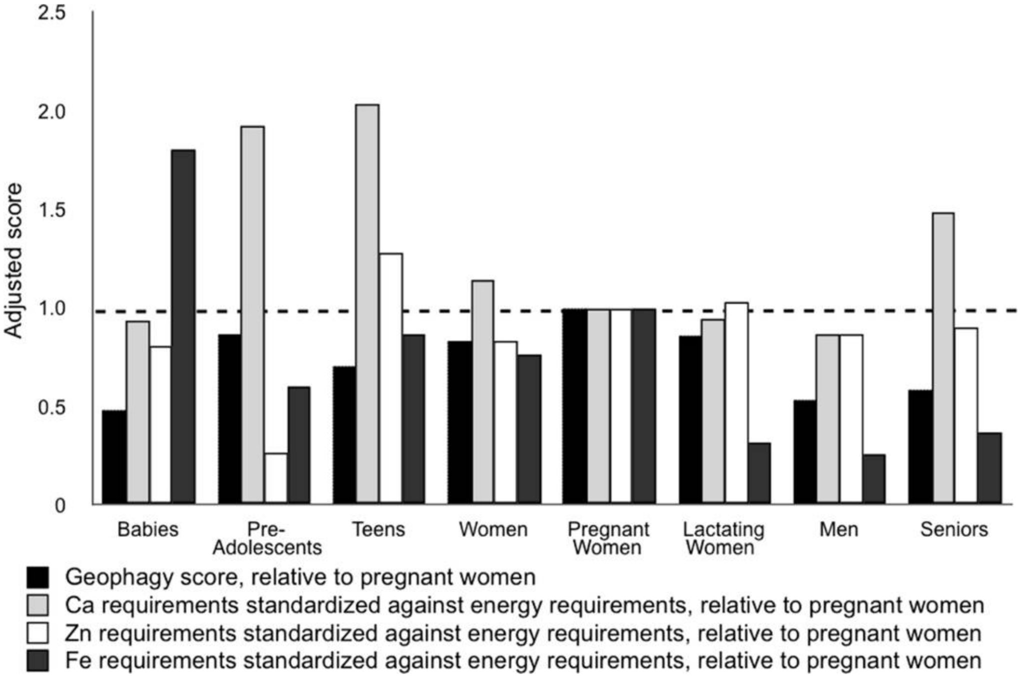


Figure 4. Geophagy Score and Selected Nutrient Requirements, by Life Stage
All values have been standardized against those for pregnant women for ease of comparison

If geophagic earth were consumed to obtain calcium, as Wiley and Katz (1998) proposed, one would expect preadolescents, adolescents, and the elderly, who have the highest calcium requirements, to engage in geophagy most frequently. If zinc deficiency were the impetus for geophagy, it should occur uniformly among all categories of adults, because they have similar zinc requirements. And, if earth were consumed to obtain iron (Hunter 1973; Abrahams 1997), we would expect infants and pregnant women to ingest earth most frequently. However, nutrient requirements were not significant predictors of geophagy scores for calcium (Spearman's rho 0.332, p=0.422), iron (Spearman's rho 0.542, p=0.165), or zinc (Spearman's rho 0.267, p=0.523). Thus, occurrences of geophagy do not parallel requirements for any of these three nutrients (Figure 4).

If geophagy were a response to nutrient deficiency, then pregnant women should consume earth most often late in gestation, when nutrient requirements are highest. Women need less iron in early pregnancy than they do when not pregnant because they are not experiencing menstrual blood loss, but later in pregnancy women's iron requirements are higher than when not pregnant because of the needs of the developing fetus (Institute of Medicine 2002). Women also need less calcium early in pregnancy compared to later, because fetal skeletal growth accelerates in mid-pregnancy; most of the calcium used by the fetus is accumulated during the third trimester (Institute of Medicine 2002). Zinc requirements do not change markedly throughout pregnancy (Institute of Medicine 2002). Our data indicate that geophagy occurs nearly twice as frequently in early pregnancy as in late pregnancy (Figure 5). This pattern is not predicted by the nutrient deficiency hypothesis.

Nutrient Content of Geophagic Earth

If geophagy were an adaptive response to nutrient deficiencies, we would expect geophagic earth to contain the nutrients that are in short supply. Unfortunately,

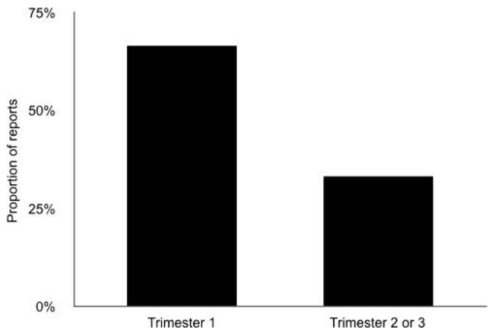


Figure 5. Timing of Geophagy During Pregnancy (n=15)

available information only enables us to evaluate this corollary for iron, and then only incompletely. Red color, indicative of the presence of iron, was reported in less than half the soils that were eaten (70 of 158; Figure 6a). Strikingly, when there was a choice between red clays and clays of other colors, the non-red clays were preferred (six of eight reports). For example, the Luo people of Kenya and Tanzania preferred the white clay sold at the market to the reddish clay that could be collected locally (Geissler 2000) and in the U.S. (Alabama), white clay was preferred over red clay (Spencer 2002). According to Vermeer (1971), the Ewe people of Ghana actually remove iron from red clay soils before consumption.

In the geophagy literature, it has been common to measure only the total elemental composition of geophagic soils (typically using acid digests). This is problematic because acid digests alone ignore much of the body's biochemistry, most critically, the pH of the intestine, the site of most elemental nutrient absorption. Because intestinal pH is much higher than the stomach, and nutrients are more soluble at low pH, equating the total elemental composition with the amount available to cross an organism's cellular membranes—i.e., its bioavailability (Semple et al. 2004)—vastly overestimates the usable nutrient content (Wilson 2003). Therefore, methods that involve only an acid digest can merely indicate if there is any element of interest present; the establishment of bioavailability requires more sophisticated techniques (Young et al. 2008).

Only five in vitro studies of geophagic samples have considered intestinal biochemistry in their analyses of bioavailable nutrients. Two of these used the physiologically based extraction test, which includes a phase that mimics the pH and digestive enzymes in the gut, to study Ugandan (Smith et al. 2000) and Indian geophagic soils (Abrahams et al. 2006), respectively. In these studies, less than 5% of the total iron present was bioavailable. Negligible amounts of other biologically necessary minerals, including zinc, were available.

Kikouama et al. (2009) investigated trace elements released by six West African geophagic clays under conditions that mimicked the oral, gastric, or intestinal environment (samples were not passed through each stage consecutively). They found the availability of both ferric and ferrous iron to be lowest under intestinal pH, but did not calculate potential iron contribution.

A fourth in vitro study that attempted replication of intestinal conditions was conducted on two samples of South African geophagic soils (Dreyer et al. 2004). Earth was added to iron-enriched Ringer's lactate solution and the precipitation of elements at gastric and intestinal pH was measured. Black geophagic earth adsorbed sodium, potassium, and iron and liberated calcium and magnesium at pH 6.2. Iron from the Ringer solution was absorbed by

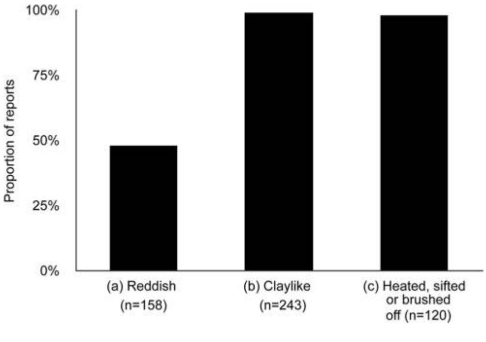


Figure 6. Description of Geophagic Soils Showing Frequency of Reports Discussing (A) Color, (B) Texture, and (C) Preparation

the red geophagic earth at pH 6.2; no change in other elements was seen. In short, neither South African sample provided iron or zinc, but one might provide calcium.

Hooda et al. (2004) conducted the most thorough study of bioavailability because they not only examined the nutrients that geophagic materials could contribute in vitro, but their capacity to bind nutrients in suspension, thus rendering them unavailable. Results indicated that the five geophagic samples from around the world provided bioavailable calcium, magnesium, and manganese, but significantly reduced the availability of iron and zinc in suspension, suggesting that geophagic earth does not contribute these nutrients and is in fact likely to bind the iron and zinc available in ingested foods.

Most of the in vivo studies of the effects of geophagy on micronutrient absorption used outdated methods, small sample sizes, and were not adequately statistically analyzed (Young 2010). However, the limited data they do offer suggest that geophagy either decreases or does not alter micronutrient status, rather than increasing it.

Briefly, Minnich et al. (1968) demonstrated that the mean proportion of iron absorbed by people who ingested 5g of Turkish soil together with either radio-labeled iron sulfate or radio-labeled heme iron decreased by 9%. These results were subsequently replicated using other Turkish soils by members of the same research group (Çavdar and Arcasoy 1972). Talkington et al. (1970) tested the impact of two popular Texan geophagic clays on radio-labeled iron absorption and found a 1 to 3% increase in iron absorption in the presence of clay. This difference is unlikely statistically significant. Sayers et al. (1974) studied iron absorption among five habitual geophagists in South Africa. ^{55}Fe ascorbate absorption was greatly decreased when 250g of geophagic earth from participants' own supplies was eaten (mean absorption was 17.4% without earth versus 5% with earth).

In a study of 17 Turkish children, the 12 geophagists demonstrated impaired iron and zinc absorption compared to the five non-geophagists (Arcasoy et al. 1978). A second study of zinc absorption, in the presence and absence of 5g of geophagic clay, also indicated that clay impeded zinc absorption (Çavdar et al. 1983). The authors suggested that earth might bind not just with dietary zinc, but also with endogenous zinc released from the pancreas. In studies of rats, Smith and Halsted (1970) determined that modified Iranian geophagic soil could contribute dietary zinc. These results contrast with bioavailability data from in vitro analyses of unadulterated geophagic earth (Dreyer et al. 2004; Hooda et al. 2004; Abrahams et al. 2006), which indicated that little zinc was available and that some geophagic earth samples bound dietary zinc, rendering it unavailable. Finally, in the most recent in vivo study of the binding capacity of clays, pregnant rats were fed varying amounts of clay in a nutritionally complete diet (Edwards et al. 1983). The rats as well as their pups suffered skeletal and fur changes and slowed development, but exhibited no differences in hemoglobin or red blood cell count after 60 days; other nutrient indices were not evaluated. This suggests that some nutrients may have been chelated, but the data are inconclusive. Based on these few, small experimental studies, we can conclude that some geophagic clays interfere with absorption of cations, which can, in turn, result in nutrient deficiencies.

In sum, few of the available data support the hypothesis that geophagy functions to ameliorate mineral nutrient deficiencies. In fact, if clays bind dietary nutrients, this could help to explain the association between geophagy and anemia: eating certain earth might actually cause nutrient deficiencies. It is important to note, however, that presently available data on iron and zinc bioavailability are limited in quality and quantity, and information on the bioavailability of calcium and other minerals is fragmentary. More research is needed in this area.

Geophagy After the Resolution of a Deficiency

If geophagy were a response to nutrient deficiency, the resolution of that deficiency should result in cessation of the behavior. Although the literature is not extensive enough to rigorously test this corollary, there have been a few studies that assessed the effect of resolving a nutrient deficiency on pica behavior.

Three single-blinded studies suggested that iron supplementation resulted in cessation of pica behavior, including geophagy (McDonald and Marshall 1964; Mohan et al. 1968; Rogers 1972). However, there were numerous problems with the study designs, including a lack of controls, small sample sizes, and poor measurement of iron status, all of which make it impossible to attribute behavioral changes to iron supplementation alone (Reid 1992; Young 2010).

There have been two controlled double-blind studies of iron supplementation and pica. In the first (Gutelius et al. 1962), no correlation was found between changes in hemoglobin concentration and changes in pica. In the second study (Nchito et al. 2004), which focused specifically on geophagy rather than pica more generally, neither randomization to 10 months of iron supplementation nor 10 months of multivitamins significantly reduced geophagy among 402 Zambian schoolchildren. Based on multivariate logistic models, the authors concluded that neither iron supplementation nor multi-micronutrient supplementation were significant predictors of geophagy ($p=0.44$, $p=0.88$, respectively). Thus, experimental data do not support the hypothesis that changes in iron status alter geophagic behavior.

There have been three studies investigating the effects of zinc supplementation on pica behavior (Bhalla et al. 1983; Chen et al. 1985; Lofts et al. 1990). Pica decreased after administration of zinc in all three, but it is not clear that this was attributable to the zinc supplementation because there was no indication of other messages given to the subjects, no controls, and no evidence of increase in zinc levels of subjects in two of the three studies (Bhalla et al. 1983; Chen et al. 1985). In sum, available data are insufficient to permit conclusions about the efficacy of zinc supplementation in causing cessation of pica (Young 2010).

In the sole study of the effects of calcium (Gutelius et al. 1963), experimental supplementation had no effect on pica behavior.

ADAPTIVE HYPOTHESIS 2: PROTECTION

Association with Gastrointestinal Distress

The protection hypothesis predicts that geophagy should often be associated with gastrointestinal distress. Indeed, geophagy was associated with symptoms of gastrointestinal malaise (e.g., diarrhea, stomach pain, flatulence) in 48 of the 50 (96%) reports in which the occurrence of gastrointestinal distress was recorded (Figure 3b). This is significantly higher than would be predicted by the null hypothesis that there is no difference in geophagy by gastrointestinal malaise ($p<0.001$).

Clay Content of Earths

Consistent with the protection hypothesis, geophagists are highly selective about the earth they eat. In 237 of 243 cultural reports (98%) with descriptions, geophagic earth was described as clay-like (Figure 6b). Geophagists regularly expressed preferences for earth that was clay-like or smooth rather than gritty or sandy (e.g., von Humboldt et al. 1821; Beccari 1904; Vermeer and Frate 1979). Individuals sometimes went to great lengths to obtain clay-rich earth. They were willing to walk many kilometers to reach a site where a deposit of appropriate clay occurred (e.g., Forsyth and Benoit 1989). Even among clay-rich earths, there were explicit favorites. For example, one husband who dug clay for his wife from a deposit that was closer to home and less public than her preferred site; after she tasted it, she sent him back to get the *exact* clay she craved (Finger 1993).

Pathogen Content of Geophagic Earths

Under the protection hypothesis, geophagic earth should not be a vector for the transmission of parasites and other pathogens. However, parasitic infections, especially by geohelminths, have sometimes been attributed to geophagy (Hooper and Mann 1906; Anell and Lagercrantz 1958; Halsted 1968; Glickman et al. 1999). Although the parasite and pathogen contents of ingested earth were not quantified in the cultural reports in our database, there are three reasons to believe that geophagic soils typically are not vectors of geohelminth transmission.

First, geophagists typically select subsoils that are less likely to contain geohelminth eggs than earth closer to the surface, where defecation occurs (Young et al. 2007). Second, geophagists carefully prepare the earth they eat. In 118 of 120 cultural reports (98%), geophagic soils were heated, sifted, dried, or brushed off prior to consumption, rather than being excavated and immediately consumed (Figure 6c). Indeed, in Indonesia, Ghana, India, and Guatemala, an industry developed around geophagy that involved excavators, traders, and vendors (Anonymous 1881; Hooper and Mann 1906; Vermeer 1971; Hunter et al. 1989). In other places, clay preparation is handled on an individual basis, either by the consumer or someone else in the household. Whether on a large or small scale, the preparation of geophagic earth usually involves: (1) removing impurities by crushing the earth and then sifting out sand and small stones, picking off the outer crust of earth, or sometimes sieving it through cloth; and (2) baking, frying, sun drying, or smoking the earth. These preparation practices likely kill most endoparasites and other pathogens.

Third, there is little evidence to support the transmission of hookworm by geophagy (Gelfand 1945; Heymann 2004), especially since hookworms are spread transdermally. There is conflicting evidence about whether geophagy might be a mechanism of transmission of whipworms (*Trichuris*) or roundworms (*Ascaris*). None of the prepared geophagic earths from Tanzania sampled by Young et al. (2007) contained live geohelminths, but in two other studies (Wong et al. 1991; Geissler et al. 1998), viable helminths were discovered in geophagic soils. This difference may be explained by the latter being conducted on soils eaten by children, who may have been more careless than adults about preparing the soil before consuming it (Young et al. 2007).

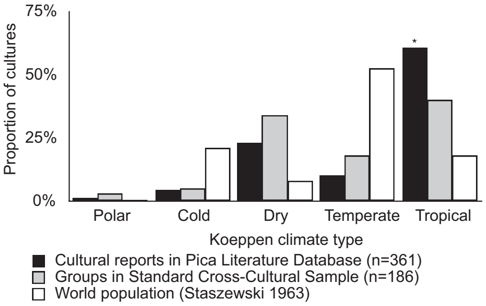


Figure 7. Distribution of Geophagic Cultures in the Pica Literature Database (See Also Figure 1), Standard Cross-Culture Sample, and World Population Distribution by Climate Type

The proportion of cultures in tropical areas that practice geophagy is significantly higher (*) than would be predicted by either the distribution of cultural groups in the SCCS or the worldwide population distribution by climate region ($p<0.0001$).

Geophagy by Climate Type

The protection hypothesis predicts that individuals who are frequently exposed to harmful foodborne microbes should frequently engage in geophagy. Foodborne pathogens multiply rapidly in hot, humid, tropical climates (Hui et al. 2001a), and species of pathogens and infectious diseases are more diverse in equatorial areas than in more northern latitudes (Guernier et al. 2004). Thus, we would expect geophagy to occur most frequently at low latitudes and altitudes. Although geophagy occurs throughout the world (Figure 1), it is especially common in tropical climate zones and exceedingly rare in polar and cold climates (Figure 7). The proportion of cultures in tropical areas that practice geophagy is much higher than would be predicted by either the distribution of cultural groups in the SCCS ($p<0.0001$) or the worldwide population distribution by climate region ($p<0.0001$).

Geophagy and Susceptibility to Toxins and Pathogens

Under the protection hypothesis, people should engage in geophagy when they are most susceptible to the harmful effects of toxins, parasites, and other pathogens. Particularly susceptible life stages are those during which rapid growth and cell division is occurring (i.e., embryogenesis and preadolescence; Bearer 1995). Furthermore, pregnant women are adaptively immunosuppressed (to avoid rejecting the embryo), so avoidance of parasites and pathogens is especially important for the woman's own health during pregnancy (Flaxman and Sherman 2000). Therefore, within a culture in which geophagy occurs, the hypothesis predicts that it should occur more frequently among pregnant women and children than among any other age or sex groups.

Indeed, the data indicate that pregnant women and preadolescents consumed earth most frequently (Figures 2 and 4). In multilevel, mixed-effect regression models of geophagy score, in which life stage is one of the independent variables and pregnant women is the reference level, the beta coefficients for all other life stages are significantly smaller. In other words, pregnant women consumed earth significantly more often than any other life stage group ($p<0.0001$). Thus we can reject the hypothesis that life stage cannot predict geophagy behavior.

In fact, there are more total reports of geophagy in pregnant women than reports of geophagy for all other life stages combined. Geophagy is so closely associated with pregnancy that the consumption of earth has been termed "a sign of the commencement of pregnancy" (Hooper and Mann 1906:254). In many countries, geophagy is thought of as a behavior unique to pregnancy, e.g., "It would be very surprising if pregnant women in Malawi did not eat clay. That's how you know when you are pregnant!" (Hunter 1993:75).

The protection hypothesis further predicts that geophagy should be more frequent early in pregnancy when embryonic tissues are most susceptible to damage from teratogens (Moore and Persaud 1998; Flaxman and Sherman 2000). Consistent with this, 10 of the 15 accounts that discussed the timing of geophagy during pregnancy indicated that consumption occurred during the first trimester (Figure 5).

NON-ADAPTIVE HYPOTHESIS 3A: HUNGER

If geophagy were a non-adaptive behavior that occurs when a famished person attempts to fill an empty stomach, we would expect it to occur most often in times of food shortage or famine. We located data on hunger status of geophagists in 72 cultural reports (Figure 3c). Among these reports, geophagy was attributed solely to hunger in only 16 (22%). In contrast, hunger was explicitly not associated with geophagy in 36 reports (50%). In some of these reports, the adequacy of the food supply of geophagists was commented on directly by observers (Buckingham 1842) or indicated indirectly through discussion of the obesity of geophagists (e.g., Vermeer and Frate 1979) or the wealth of those who consumed earth (e.g., Gautier and McQuoid 1853; Livingstone and Waller 1875). In the remaining 20 reports (28%), earth was sometimes eaten out of hunger while other times for "pleasure," "custom," "craving," or "habit" (e.g., von Humboldt et al. 1821). This distribution is significantly different ($p<0.006$) than would be expected under the null hypothesis.

The relative frequencies of geophagy by various sex and age groups (Figure 2) and its timing within pregnancy (Figure 5) also offer no support for hunger motivating geophagy. For example, men and non-pregnant women have similar caloric requirements and so would be equally likely to engage in geophagy under this hypothesis. However, women practice geophagy much more often than men. Pregnant women require more calories (and are thus more likely to be hungry) late in pregnancy when the embryo is large and growing rapidly than early in pregnancy (Institute of Medicine 1990). Yet geophagy occurs more commonly in early than in late gestation (Figure 5). Finally, lactating women have the greatest caloric requirements of all the groups (Institute of Medicine 1990) and are therefore likely to be hungry most often. However, they are not the most frequent geophagists.

Earth Selection and Preparation

Under the non-adaptive hypothesis, if earth were being eaten simply to fill an empty stomach, any sort of earth (or any other non-toxic substance) should do. However, consumers were highly selective about the earth they ate (Figure 6). Indeed, we did not find a single report in which any type of earth was desired. Of the 77 cultural reports that mention how people felt about the earth they were eating, 72 (93%) explicitly discussed their desire for specific types of earth (Figure 3d), usually clay-rich soils. If earth was consumed as a last resort in the face of hunger, we would not expect descriptions such as “a devouring passion” (Galt 1872:403), “enjoyed” (Walker 1910: 220), and “great attachment” (Shannon 1794:375).

Quantity Consumed

Finally, if hunger motivated geophagy, we would expect that enough earth would be eaten to sate the appetite, i.e., to fill the geophagist’s stomach. Although most reports did not quantify the amount of earth consumed, many described it qualitatively. The amount usually was small, for example: “a few morsels” (Maupetit 1911:179), “size of a hazelnut” (Garnier 1871:283), and “lump the size of an egg” (Whiting 1947:611). In 11 reports, the amount of earth was weighed. The modal amount that an individual consumed was approximately 30g, although in three cases more than 100g was reportedly eaten. Recently, more rigorous biomedical studies have recorded consumption of 30–50g of earth per individual (Geissler et al. 1997; Saathoff et al. 2002; Luoba et al. 2005; Young et al. 2010). The implication is that the usual amount of earth consumed is small, more like a medicament than a meal. Although clays can expand in volume in a moist environment, it is unlikely that the small quantities ingested would quell hunger pains, and certainly not for very long since geophagic earth provides no energy.

NON-ADAPTIVE HYPOTHESIS 3B: EPIPHENOMENON OF NUTRIENT DEFICIENCY

If geophagy were a non-adaptive epiphenomenon of nutrient deficiencies, we would expect the behavior to be associated with such deficiencies. In our database, anemia and geophagy are associated, but the cross-sectional nature of the data do not permit determination of temporality. If, however, a deficiency caused geophagy, the cessation of geophagy should occur upon supplementation with deficient nutrient. This is usually not the case (see the earlier section, Geophagy After the Resolution of a Deficiency). Research on the neurological and sensory consequences of nutrient deficiencies is lacking, but with current data, there is little support for this hypothesis.

Geophagy in Non-human Animals

Geophagy also occurs in a wide range of non-human vertebrates (see supplementary material, Tables 2 and 3, available at http://journals.uchicago.edu/QRB). We located 79 accounts of its occurrence in 57 species of primates (Table 2) and 251 accounts of geophagy in 240 species of other vertebrates (Table 3), including mammals (in 29 families), birds (in 13 families), and reptiles (in five families). Geophagy is likely far more common, but has gone unnoticed because detailed, long-term observations of that species’ dietary habits have not been made.

Among primates, multiple hypotheses for geophagy have received empirical support. Krishnamani and Mahaney (2000:899) concluded that “mineral supplementation, adsorption of toxins, treatment of diarrhoea and pH adjustment of the gut seem the most plausible reasons why primates engage in geophagy.” In our tabulation of primate geophagy (Table 2), 49 of 79 accounts described geophagy as an adaptive behavior, and in the other 30 accounts, the probable function of geophagy was not specified. Among the adaptive reports, 32 (65%) attributed geophagy as probably or definitely motivated by the detoxification of plant secondary compounds or protection from parasites and pathogens (including treatment of diarrhea), and 32 (65%) attributed geophagy as probably or definitely related to obtaining nutrients. The proportions sum to more than 100% because some authors proposed multiple explanations. The vast majority of primates in which geophagy has been observed inhabit tropical areas, and detoxification was inferred most commonly in leaf- and fruit-eating primates. Ingested earth most frequently came from the forest floor and termite mounds, and often was described as having a clay-like consistency.

Among vertebrates other than primates (Table 3), 176 of the 251 accounts (70%) indicated that geophagy was definitely or probably an adaptive behavior, whereas only 5 (2%) indicated that it was non-adaptive. In the other accounts the probable function of geophagy was not specified. Among the adaptive reports, 88% attributed geophagy to obtaining mineral nutrients (primarily salt and calcium) and 19% attributed geophagy to detoxification of plant secondary compounds. The proportions sum to more than 100% because some authors proposed multiple explanations.

The possibility that geophagy provides protection from parasites and pathogens was rarely considered in non-primates, and the sex and reproductive status of geophagists were infrequently mentioned. However, geophagy was described by sex and pregnancy status among 17 species of neotropical, fruit-eating bats (Bravo et al. 2008, 2010). Intriguingly, females engaged in geophagy more often than males, and pregnant females did so more often than non-pregnant females.

Studies with laboratory animals indicate that geophagy can provide relief from gastrointestinal distress. Rats cannot rid themselves of toxins through emesis, but when they are poisoned experimentally they preferentially ingest kaolin, which reduces poison-related morbidity and mortality (Mitchell et al. 1976; Burchfield et al. 1977; Watson et al. 1987; Takeda et al. 1993; Madden et al. 1999). Similar results were observed in experiments on parrots (Gilardi et al. 1999).

Animal geophagy has been observed in a wide range of climate and habitat types, although the majority of studies (especially of birds) were conducted in the tropics. Geophagy was most often detected during observations at traditionally used "clay licks," "mineral licks," and "salt licks," and need for nutrients (especially sodium and calcium) was most commonly inferred as the function of geophagy (especially in ungulates). Detoxification was inferred primarily in tropical, fruit-eating birds such as parrots and pigeons. However, the soils at many of the traditional mineral licks were described as clay-rich in composition, so detoxification and protection against pathogens may be more common than is currently recognized. Indeed, some studies (Tables 2 and 3) attributed geophagy to both detoxification and micronutrient acquisition.

CHALLENGES TO THE INTERPRETATION OF DATA

There are several reasons for caution in interpreting our results. First is the danger of underreporting, which is inherent in any literature review. Human and animal geophagy is unquestionably underreported because it is easily missed, even by trained observers. In humans, geophagists and local informants may attempt to conceal the behavior for fear of being judged negatively or chastised, or because earth eating may be interpreted as an indication of pregnancy status (which some may want to keep private), poverty, or lack of self control (Hooper and Mann 1906; Dickins and Ford 1942; Sayetta 1986). Even when geophagists are not furtive, investigators may not know to inquire about earth eating specifically, and they "discover" geophagy only by accident (e.g., Hooper and Mann 1906; Vermeer 1966; Cooksey 1995; Rainville 1998; Grigsby et al. 1999).

Second, for human geophagy, there is considerable variability in objectivity and thoroughness among studies. Although judgmental language is stripped from our database, we wonder if the revulsion geophagy sometimes elicits has colored published reports by limiting the amount of information investigators pursued or were given in the course of fieldwork. Preconceived notions about who engages in geophagy may have also biased some of the reports. For example, if geophagy was attributed to "the weaker sex" (Maler 1692), the observer might not try to find out how often men practiced geophagy.

Third, there is an additional difficulty in studying human geophagy, and pica in general: it does not easily fit into a specific cultural conceptual category. From a cultural perspective, the people being interviewed may think of pica substances as medicines, food additives, or just cravings, and food recall questionnaires generally do not probe these issues with appropriate prompts (Young and Ali 2005). Thus, because we can only report on positive observations of geophagy, there are likely to be some false negatives (Type 2 errors), i.e., societies in which geophagy occurs, but has not been documented.

Fourth, in humans some misclassification errors probably occurred (see Methodology). However, classifying a pregnant woman as non-pregnant or an anemic person as non-anemic would only weaken the trends we discovered. And misclassification, underreporting, or false negatives would not explain the significant differences we documented among categories of geophagists within societies, including the relationships between geophagy and anemia (Figure 3a), gastrointestinal distress (Figure 3b), the predominance of the behavior among pregnant women and children (Figure 2), or the occurrence of geophagy in early pregnancy (Figure 5).

Discussion

Three hypotheses have been proposed for the functional significance of human geophagy. Of these, the non-adaptive hypothesis that geophagy is an attempt to fill a hungry stomach explains few cases. Geophagy occurs when food is plentifully available. Moreover, that small quantities of earth are consumed, the age and sex biases, and the frequent association with strong cravings for specific types of earth are not consistent with the hunger hypothesis. The second non-adaptive hypothesis, that geophagy is an epiphenomenon of nutrient deficiencies that cause neurological or sensory problems, also is not supported by available data. Nutrient supplementation does not regularly cause the cessation of geophagy.

The first adaptive hypothesis is that geophagy results from nutrient deficiencies. Seemingly consistent with this hypothesis, geophagy is frequently associated with anemia. However, the timing of geophagy does not parallel the timing of changes in nutrient needs through the life span, nor within pregnancy. The irregular presence and low bioavailability of calcium, zinc, and iron in geophagic earth, the fact that iron supplementation does not reduce geophagic behavior, and the experimental data indicating that micronutrient absorption is limited after the consumption of earth cast doubt on this hypothesis.

The second adaptive hypothesis is that geophagy is a mechanism of protection against plant toxins, parasites, and other pathogens. Consistent with this hypothesis is the association of geophagy with gastrointestinal distress and with consumption of toxic substances, the high clay content of most geophagic soils (clay adsorbs dangerous chemicals and pathogens), the occurrence of geophagy in areas of the world with the highest parasite and pathogen densities (the tropics), and the sex bias and timing of geophagy during periods of greatest susceptibility to harm from parasites, pathogens, and toxins (childhood and early in pregnancy).

Use of clay in food preparation is a well-known means of neutralizing toxins (Johns and Duquette 1991; Johns 1996). In 27 reports in the Pica Literature Database, clay was used in the preparation of major food items, e.g., staple crops and fish (honey, salt, or oil were not considered major food items). In ten of these cultures (37%), clay was used in the preparation of or eaten with foods that contain harmful substances, such as Andean potatoes (which contain glycoalkaloids; Johns 1996) and Sardinian acorns (high in tannins; Wagner and Cortes 1921;

Usaï and Mazzarella 1969). In Western Australia, aborigines used clay in the preparation of *mene*, a tuber known to cause diarrhea when ingested raw (Grey 1841). Several of the cultural reports in our database contained explicit information about the association of geophagy with exposure to toxins. For example, people in the Northern Territory of Australia explained that they ate clay to "line the stomach" before eating fish they knew to be poisonous (Grey 1841).

The detoxifying properties of clay may even explain some of the geophagy that has been observed in times of food shortages (Figure 3c). When people are forced to eat plant parts they would normally avoid due to the secondary compounds they contain (e.g., weed stems, bark, and roots), consumption of small amounts of clay could reduce the dangers associated with ingesting these marginal foods by binding with the toxic chemicals that typically make them unpalatable (Johns 1996).

Occurrences of geophagy in non-human primates and other vertebrates also support the two adaptive hypotheses over the non-adaptive alternative. However, no conclusions can be drawn about the relative importance of micronutrient deficiencies versus protection against plant toxins in the occurrence of non-human geophagy, primarily because the possibility that geophagy provides protection against parasites and pathogens was rarely considered for non-primates. In primates, geophagy was attributed to protection from toxins and to micronutrient deficiencies with approximately equal frequencies (Table 2), whereas in other vertebrates geophagy was typically attributed to nutrient deficiencies (Table 3). Whether this apparent difference is real is impossible to determine because many studies of primates specifically considered the protection function of geophagy, whereas most studies of other vertebrates did not. The frequency with which geophagy was reported in tropical leaf- and fruit-eating birds and mammals suggests that detoxification of plant secondary compounds is a more important function of the behavior than presently is realized.

If protection from pathogens and detoxification of plant secondary compounds are the primary functions of geophagy, what do we make of the strong and consistent associations between geophagy and anemia in humans? There are two possibilities, both of which pertain to the complex and delicate balance between iron status and infection. Anemia can be an adaptive bodily response to infections, a nutritional adaptation whereby the sequestration of certain nutrients can protect against pathogenic agents (Prentice et al. 2007; Wander et al. 2009). Many foodborne bacteria require iron to reproduce and iron sequestration reduces bacterial growth rates. Under this hypothesis, the relationship between anemia and geophagy is correlational but not causal, that is, both the ingestive behavior and the physiological response are adaptations to minimize the severity of foodborne bacterial infections.

The second possibility is that ingestion of geophagic earth not only inhibits parasites and other pathogens but also impedes iron absorption, either by binding with dietary iron directly (Hooda et al. 2004) or with the mucin layer in the small intestine (Leonard et al. 1994) thereby making it difficult for bound iron molecules to pass through the brush border. Under this scenario, the relationship between geophagy and anemia is causal—i.e., geophagy causes anemia as a side effect of its anti-parasite/pathogen benefits. Information that is presently available is insufficient to decide between these alternatives. Regardless of which is correct, the anemia-geophagy correlation could be consistent with the protection hypotheses.

Further tests of the two adaptive hypotheses would be useful. In terms of the protective hypothesis, it would be illuminating to compare the amounts and toxicities of plant secondary compounds and foodborne parasites and pathogens in the diets of geophagic and non-geophagic human societies and animal species, and among individuals within those societies or populations. Exposing laboratory animals to biotic enemies and toxins, and then feeding them geophagic earth or a placebo would also help quantify the protective effects of geophagic soils. A third test of this hypothesis would be to establish the capacity of geophagic earths to bind harmful toxins, pathogens, and endoparasites in in vivo conditions.

We hope this paper stimulates such research. More importantly, we hope readers agree that it is time to stop regarding geophagy as a bizarre, non-adaptive gustatory mistake. Our data indicate clearly that geophagy is a widespread behavior in humans and other vertebrates that occurs during both vulnerable life stages and when facing ecological conditions that require protection.

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