

Starting from the Source

Methods and Priorities for Explaining Lead Exposure

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Abstract

Lead is a dangerous neurotoxin, and lead poisoning remains one of the most serious and neglected public health challenges in the developing world, with major negative impacts on global health, education, and overall economic development. There is now growing international momentum to mitigate lead pollution, with the goal of dramatically reducing human lead exposure and consequent adverse effects. Yet before lead exposure can be effectively mitigated, it is essential to understand *why* humans are being exposed to lead in the first place and therefore *how* policymakers can intervene to stop further exposure. To date, such research into the major sources of lead exposure—broadly referred to as *source assessment*—in developing countries has been limited. Thus, there is limited information and no global scientific consensus about the most important causes of global lead exposure.

Given growing global interest in addressing lead poisoning, there is an urgent need to better understand the major sources of lead exposure in different settings by increasing the volume and quality of related research. Tailored to a policy audience, this paper offers a state-of-the-science review of methods for doing so. First, it provides background for understanding lead exposure—that is, how and why lead enters the environment, how it behaves once there, and how environmental lead results in elevated blood lead levels for humans. Second, it outlines basic principles for source assessment, including a discussion of objectives and terminology. Third, it details the range of methods available for understanding the sources of lead exposure and describes how such methods can be used in combination to understand major sources of lead exposure in a given context. Finally, it considers major policy-relevant gaps in the literature base about sources of global exposure and offers suggestions for a research agenda in this space.

Starting from the Source: Methods and Priorities for Explaining Lead Exposure

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Center for Global Development

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Introduction

Lead is a dangerous neurotoxin, and lead poisoning remains one of the most serious and neglected public health challenges in the developing world. Globally, about one in three children have blood lead levels (BLLs) above 5 micrograms per decilitre ($\mu\text{g}/\text{dL}$)ⁱ—a reference level at which the World Health Organization (WHO) recommends public health intervention.ⁱⁱ The burden is overwhelmingly concentrated in low- and middle-income countries (LMICs), where lead poisoning results in severe detriments to global health, education, and overall economic development. Recent estimates suggest that lead exposure causes between 1.6 and 5.5 million deaths each year from cardiovascular disease;ⁱⁱⁱ in parallel, lead impairs children’s cognitive development, explaining an estimated 20 percent of the difference in learning levels between rich and poor countries.^{iv}

Historically, there has been very low awareness about the extent and severity of global lead poisoning in LMICs among policymakers and the general public. However, in recent years—following the 2020 publication of the landmark report, *The Toxic Truth*, by UNICEF and Pure Earth^v—global lead poisoning has begun to receive increased international recognition as a major development challenge.^{vi} There is now growing momentum among philanthropies, development partners, and some national governments to mitigate lead pollution, with the goal of dramatically reducing human lead exposure and consequent adverse effects.

Yet before lead exposure can be effectively mitigated, the *causes* of lead exposure must first be identified; that is, policymakers, aided by scientists, must identify *why* humans are being exposed to lead in the first place, and therefore *how* they can intervene to stop further exposure. These *sources* of lead exposure—the industries, products, or infrastructure from which lead exposure originates—vary dramatically between geographic areas, socioeconomic groups, and even individuals. In some cases, a single dominant source might explain the vast majority of lead exposure for an individual or population; in others, many different sources might contribute to the overall burden. The process of tracking down one or more sources of lead exposure in any given population is often referred to as *source assessment* or *source apportionment*.¹

Because lead has been widely used in industry, consumer products, and infrastructure throughout history, there are many possible sources of lead exposure for any given population. However, research into the major sources of lead exposure—both globally and within most specific LMIC settings—has been very limited. Since the phase-out of leaded gasoline, there is no global scientific consensus about the most important causes of global lead exposure, or how much any specific

1 A note on terminology: We use *source assessment* as an umbrella term for identifying sources and attributing exposure to them. Within this, we use the terms *source identification* or *risk assessment* to refer to the process of identifying sources to blame for at least some exposure, and *source apportionment* to describe the more demanding process of quantitatively attributing exposure to different sources. This distinction is further broken down and explained in Part 2.

source (e.g., battery recycling, lead paint, and so forth) contributes to the overall burden. Researchers continue to identify new industries and consumer products as sources of lead exposure in certain settings, many of which might be important on a global scale. The present list of suspected major sources includes industrial sources such as mining, smelting, and lead-acid battery recycling; consumer products and food sources such as adulterated spices, contaminated cookware, and cosmetics; and infrastructural sources such as lead paint and pipes.

Given growing global interest in addressing lead poisoning, there is an urgent need to better understand the major sources of lead exposure in different settings by increasing the volume and quality of related research. Fortunately, there is a large and growing body of appropriate methodological approaches that can be used within such research and are technically feasible and affordable in most settings. These include but are not limited to chemical analysis techniques that identify and/or quantify concentrations of lead in food, consumer products, or the environment; statistical analysis methods that evaluate associations of BLLs with risk factors and the presence of potential exposure sources; modelling methods that predict BLLs based on potential exposure sources; and isotopic analyses, which compare the composition of lead in the body to that in potential sources. These methods can be used both alone and in combination to better understand the major sources of exposure in any given setting.

Tailored to a policy audience, this paper aims to inform ongoing policy discussions about identifying and mitigating the major causes of global lead exposure, as well as addressing the research gaps required to do so effectively. It provides a state-of-the-science overview of methods to identify sources of human lead exposure and their relative importance, while also offering a prioritized research agenda for future policy-relevant scientific inquiry about sources of lead exposure. It is informed by discussions held during a Technical Roundtable on Source Apportionment and Identification of Lead Exposure, convened by the Center for Global Development on January 24, 2024.²

The remainder of the paper proceeds as follows. First, it provides background for understanding lead exposure: how and why lead enters the human-facing environment, how it behaves once it is in the environment, and the conditions and processes under which environmental lead subsequently results in elevated blood-lead levels for humans. Second, it provides basic principles for source assessment, including discussion of objectives and terminology. Third, it details the range of methods available for understanding the sources of lead exposure and how such methods can be used in combination to understand major sources of lead exposure in a given context. Finally, it considers major policy-relevant gaps in the literature base about sources of global exposure and offers suggestions for a research agenda in this space.

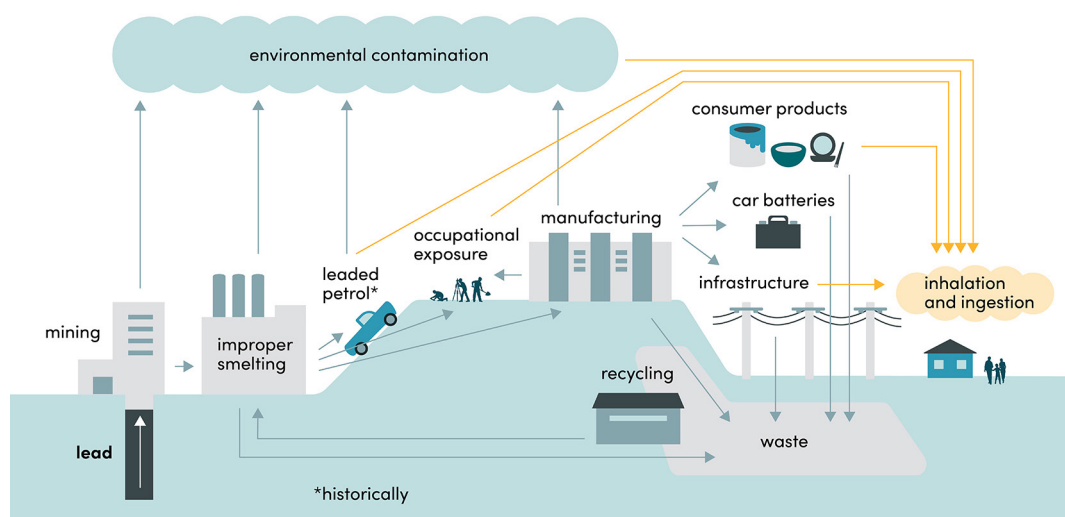
2 See Appendix for agenda and participant list.

Part 1: Understanding lead exposure

Lead is a natural, indestructible element—but the mere existence of lead, somewhere in the earth’s crust, does not itself naturally cause lead exposure. Lead can only become a *source* of human lead exposure once it enters the *human-facing* environment, in a form factor and location where it can then enter the human body. To appropriately assess potential sources of lead poisoning, therefore, it is important to first have a basic understanding of the environmental, industrial, and biological processes that can create potential pathways for human lead exposure.

In this section, we trace the life cycle of lead in the human-facing environment, explaining how and why lead exposure can occur and providing a conceptual basis for understanding the many potential sources of lead exposure. We distinguish three phases of this life cycle: first, when lead enters the human-facing environment via mining, smelting, and use within industry, infrastructure, and consumer products; second, how lead behaves once it has entered environmental media in the human-facing environment (e.g., in air, soil, and water); and third, how lead in the human-facing environment can subsequently translate to human lead exposure through ingestion, inhalation, or other exposure pathways (see Figure 1). These processes, in turn, inform our discussion of source assessment principles and methods detailed in Parts 2 and 3.

FIGURE 1. Sources and pathways of lead exposure



1.1 How lead enters the human-facing environment

During human evolution, lead was present in the environment but at a very low concentration; it is estimated that preindustrial humans had BLLs around 40 times lower than present levels in the United States, which are themselves much lower than in poorer countries or in the recent past.^{vii} However, lead is relatively common in the earth’s crust, is relatively easy to mine and refine, and

has properties that have made it highly useful to human populations throughout history (e.g., heavy weight, high malleability, pigmentation, and durability).^{viii} As a result, human populations have introduced lead into the human-facing environment since early antiquity, and primary lead mining and smelting continues to the present.

Mining—extracting lead ore from the earth’s crust into the human-facing surface of the earth—is a necessary first step in the life cycle of lead that can result in both environmental contamination and human exposure. The process of mining is itself a significant driver of exposure, both to workers and those living in proximity, as it releases substantial quantities of lead into the soil, air, surface water, and groundwater. Lead is isolated from the ore in which it is naturally found using smelting, which involves applying heat and a reducing agent to ore to extract the lead; and, subsequently, refining, by which lead bullion is purified of other remaining elements. If not properly controlled, smelting and refining processes can create toxic lead fumes, lead dust, lead-contaminated wastewater, and waste *slag* that contains a variety of toxic chemicals, including lead.

Smelting and refining processes can be further disaggregated into (1) *primary* smelting and refining of newly mined lead ore; and (2) *secondary* smelting and refining of discarded, scrap, or waste lead-containing products. The most notable source of lead for secondary smelting and refining is used lead-acid batteries (ULABs), which currently account for a significant majority (about 85 percent) of total global lead usage by mass.^{ix} Lead-acid batteries have a limited lifespan, especially in hot and humid climates and due to improper use, as is common in many LMICs; however, lead from ULABs can be almost fully recovered and recycled for use in new batteries.^{x,xi} Most lead in circulation is therefore subject to frequent, repeated secondary smelting and refining processes—in turn creating frequent, repeated opportunities for environmental lead pollution and occupational exposure.

Once mined and refined, lead can also enter the human-facing environment when it is used for a wide variety of industrial and infrastructure applications. Historically, global use of leaded gasoline led to widespread environmental contamination, primarily from automobile emissions, with lead pollution particularly concentrated along major roadways and within dense urban areas. Today, lead remains common in infrastructure such as pipes, pumps, and faucets, which can leach lead into drinking water; telecommunications cables, which can contaminate local soil and water; and paint, which can cause lead exposure during application and removal, as well as through the ingestion of paint chips and dust as it ages. Many industrial processes also rely on lead, including radiation shielding and electronics; such uses of lead may cause direct occupational exposure during use, as well as e-waste contamination once lead components have outlived their useful lifespan.

Finally, lead can directly enter individual homes, schools, workplaces, and public spaces when used in a wide variety of consumer, household, and food products. Lead is frequently found in the household within ceramics, jewellery, cosmetics, aluminium cookware, fishing weights, crystalware, toys,

ammunition, and traditional medicines, among other items; such objects can become exposure pathways if they are ingested (e.g., by children) or if they are used to prepare or serve food or beverages (e.g., ceramics, crystalware, and aluminium cookware). In some cases, individuals may also consume deliberately adulterated food or beverages, including the historical use of lead to sweeten wine and the ongoing practice of spice adulteration with brightly colored lead pigments.

1.2 How lead behaves in the environment

Lead behaves differently depending on where it is found in the environment. Broadly, there are four relevant categories of environmental lead: (1) airborne lead, (2) lead in contaminated soil, (3) lead in contaminated water, and (4) lead in other man-made objects. Under certain conditions, lead can dynamically move between environmental media; for example, lead in soil can be resuspended in air and lead in objects or soil can leach into water.

- *Air*: The fate of airborne lead particles from emissions depends on the size of particles, which varies by source.^{xii} Emissions from leaded aviation fuel are primarily in the form of ultrafine particles, which can circulate globally.^{xiii} Emissions from recycling facilities are likely to be in the form of coarser particles, which settle quickly; deposition from informal lead processing sites is generally within 100 meters, although formal smelters have been found to result in increased exposure levels 2.7 kilometers away and deposition of particles up to 250 kilometers away.^{xiv}
- *Soil*: Once settled, lead only gradually moves down the soil column, depending on soil characteristics, and can become resuspended in air.^{xv} Similarly, lead in river and lake beds can become resuspended; runoff from even historically industrial areas has higher lead concentrations than that of non-urban areas in the United States.^{xvi}
- *Water*: Lead is sparingly soluble in water, meaning that exposure from drinking water is generally from the distribution system rather than the water source itself, often from plumbing components close to the drinking valve.^{xvii} Lead is more likely to become resuspended in water and carried downstream by disturbances such as dam removal and certain precipitation events, particularly storms.^{xviii} Acidity can also increase how much lead is dissolved in water, also known as *leachability*; water acidity can also increase how much lead is absorbed into the circulatory system once consumed.^{xix,xx}
- *Objects*: Under some conditions, lead-containing objects can leach or deposit lead into other environmental media, particularly water (or food). For example, cookware containing lead, including aluminium cookware and lead-glazed ceramics, may leach lead into food, water, or other beverages. The amount of lead in cookware that may be transferred to food or water—its so-called *leachability*—is how one evaluates such cookware as a potential exposure source. Acidic food, heat, long cooking times, and pitting of pots can all increase the leachability of lead in a pot.^{xxi}

1.3 Process of exposure

There are two primary pathways—inhalation and ingestion—by which lead in the human-facing environment can enter the body. Exposure via inhalation can occur when lead dust or fumes are inhaled; this is most common in occupational settings and is thought to comprise a relatively small minority of overall lead exposure.^{xxii} Ingestion is more common, and may occur when individuals consume contaminated food, medicines, water, and other beverages; use lipstick or gloss with lead pigment; ingest larger particles of airborne lead; engage in *pica* behavior, which involves eating non-food substances such as dirt or paint chips; or incidentally consume environmental or household lead through hand-to-mouth behavior. (The latter two behaviors are particularly common among young children.) Beyond these two primary pathways, in utero fetal exposure—wherein a fetus is exposed to lead via a shared blood supply with its mother—is also common.³ Several other pathways by which lead may theoretically enter the body are thought to be relatively unusual. These include skin permeability for organic lead, which is rare since the elimination of leaded gasoline;^{xxiii} direct entry to the body through open wounds (e.g., gunshots); and entry through mucus membranes, (e.g., absorption of contaminated eyeliner through the eyes).

The quantity of lead entering the body through one or more of the pathways described above is known as the lead *intake* rate. Once lead has entered the body—typically through the lungs or gastrointestinal tract—some (but not all) lead will be absorbed into the circulatory system. The *uptake* rate, in turn, describes the quantity or proportion of lead that is absorbed into the circulatory system. Uptake rates vary by exposure pathways—inhalation or ingestion—and may be influenced by several different factors:

- *Bioavailability*: Not all of the lead entering the lungs or gastrointestinal tract enters the bloodstream. The proportion taken up by the blood depends on its *bioavailability*, which varies according to the characteristics of the lead absorbed (particularly particle size and its compound form). This is partially dependent on the *bioaccessibility* of the type of lead—its solubility in the lungs or gastrointestinal tract, which is generally measured *in-vitro*. The *relative bioavailability* of a particular type of lead measures how much is absorbed compared to a fully bioaccessible form of lead, such as lead acetate. For example, lead sulphide in the gastrointestinal tract (i.e., ingested lead) has a relative bioavailability of only 7 percent compared to over 50 percent for lead in dust and soil.^{xxiv}
- *Particle Size*: The size of lead particles is important for uptake rates both from ingestion and inhalation. In general, smaller particles result in higher absorption. An absorption fraction of around 30 percent has been assumed for battery workers, while lead from mining may be significantly less, due to the generally larger size of particles.^{xxv}

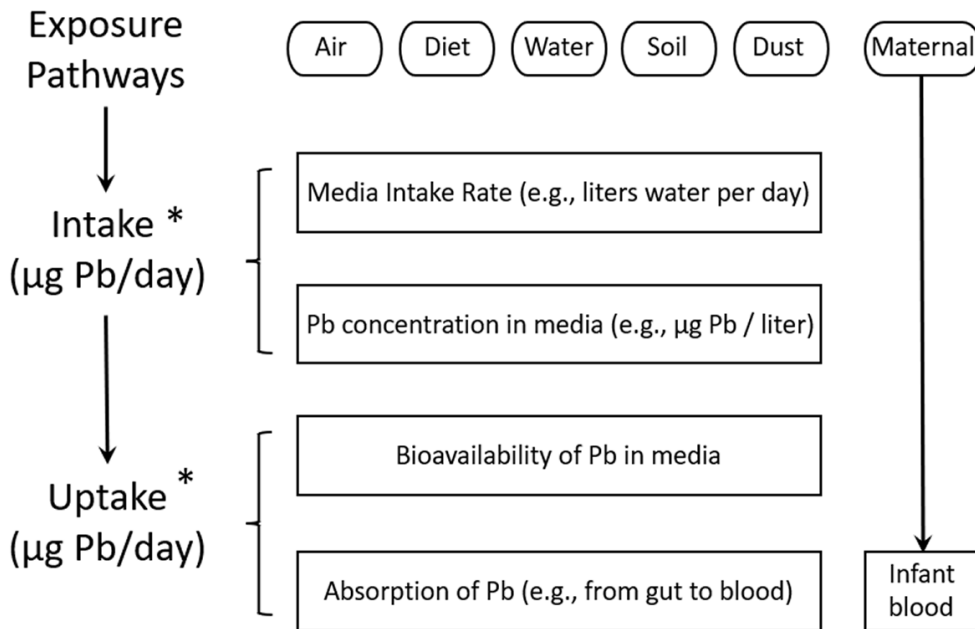
3 Elevated maternal blood lead levels may be caused by ongoing maternal exposure to lead in the environment and/or by metabolic processes associated with pregnancy, which can draw lead out from long-term storage within the skeletal system.

- *Age*: Evidence suggests that absorption of ingested lead is substantially higher for children than for adults. Estimates of absorption of ingested water-soluble lead compounds from the gastrointestinal tract range from 3–10 percent for adults, compared with 40–50 percent for children.^{xxvi}
- *Nutritional Status*: Absorption of ingested lead is much higher if an individual has not eaten for some time and somewhat higher if they are deficient in iron or calcium.^{xxvii} Nutritional deficiencies (including both malnutrition and micronutrient deficiency) are relatively common in LMICs and may contribute to significantly increased uptake of environmental lead.

Notwithstanding some individual variation, it is often possible to use intake and uptake rates from potential exposure sources, combined with measurement of lead concentrations in different media, as inputs into a model that can in turn predict BLLs with reasonable accuracy (Figure 2). This process—of predicting BLLs based on concentrations of lead in possible exposure sources—is known as *biokinetic modelling* and is further discussed in Part 3.

FIGURE 2. Inputs to biokinetic modelling^{xxviii}

Model Inputs (Intake and Uptake)



Note: *Gastrointestinal tract intake rates and absorption vary with age.

For example, a young child (ages 24–36 months) would be expected to reach a BLL of 5 µg/dL (the WHO reference level for public health intervention) if they were exposed to concentrations of lead in drinking water of 60 parts per billion (ppb), given standard water consumption levels; lead in air of 7.2 micrograms per cubic meter (mcg/m³); or 120 parts per million of lead in their diet (Table 1).

Notably, predicted BLLs do not necessarily scale linearly with increasing lead concentrations in potential exposure sources, and the predicted dose-response relationship varies somewhat by exposure source.

TABLE 1. Concentration of lead in various media required to meet certain BLL thresholds (Ages 24–36 months)^{xxix}

Medium (Regulatory Standard)	Anticipated BLL			
	2.5 µg/dL	5 µg/dL	7.5 µg/dL	10 µg/dL
Air (US EPA: 0.15 µg/m ³)	3.5 µg/m ³	7.2 µg/m ³	11 µm ³	15.2 µg/m ³
Water (WHO: 10 ppb)	28 ppb	60 ppb	96 ppb	136 ppb
Soil (US EPA: 200 ppm)	380 ppm	800 ppm	1275 ppm	1830 ppm
Diet (EU: 1.5 ppm in spice)	56 ppm	120 ppm	188 ppm	268 ppm

Part 2: Principles of source assessment

Source assessment is not a single, linear process but instead represents an umbrella term for a wide field of research with varying subjects, objectives, and methods. In this section, we provide a conceptual framework for understanding the different types of source assessment exercises, distinguishing between different pathways, subjects, and terminology.

(NB: This resource is not intended to serve as a practical guide to conducting source assessment in the field, but as a conceptual introduction to principles and methods for doing so. Those looking for further practical guidance to carry out investigations may consult UNICEF’s 2024 report, *Assessing Environmental Lead Exposure in Resource Constrained*,^{xxx} or Pure Earth’s *Home-Based Source Assessment Protocol*.^{xxxi})

2.1 Pathways of source assessment

Broadly speaking, there are two potential pathways for source assessment to follow: *top-down* source assessment, in which one or more sources are evaluated for potential harm; and *bottom-up* source assessment, which investigates the potential cause(s) of lead exposure in a specific subject population (see section 2.2). In practice, a thorough source assessment might contain elements of both directionalities, though the research questions vary slightly:

- *Top-down source assessment* starts with a specific potential source—say, lead paint or lead-glazed ceramics—and seeks to understand whether and to what extent it contributes to overall lead exposure in a population. For lead paint, for example, a top-down source assessment might ask whether lead paint is a major source of lead exposure in a given population or how much of that population’s lead exposure could be attributed to lead paint (both in absolute terms and as a percent of the overall burden). Top-down source assessments may also include multisource hazard identification, for example Pure Earth’s

Rapid Marketplace Screening,^{xxxii} which investigated lead contamination levels in 12 product categories across 25 countries. In both cases, the source assessment process starts with the (potential) sources themselves—not with the exposed population.

- *Bottom-up source assessment* starts with observed lead exposure in a specific subject population (see section 2.2) and seeks to identify the exposure source(s) for that population. For example, bottom-up source assessment could seek to identify the likely exposure source for a single acute case of lead poisoning presenting at a hospital or to explain the relative importance of several different sources in a neighborhood or region with high average BLLs.

2.2 Subjects of source assessment

For bottom-up source assessment, a second distinguishing factor is the *subject* of the exercise—that is, whose lead exposure are researchers attempting to explain? There are four broad subject categories for any given source investigation:

- *Environmental contamination*: While not explaining lead exposure per se, a source assessment process may be used to investigate the root causes of observed environmental contamination. For example, if lead is observed in drinking water, a source assessment process could be used to investigate whether lead is leaching from the ground water or water source itself, from lead pipes or water mains, or from lead fixtures (pumps or faucets) at the point of access. Likewise, a source assessment process might be used to investigate the causes of high lead contamination in soil, which might be due to legacy emissions from leaded gasoline; past or ongoing industrial contamination; or other sources, such as decaying lead paint or telecommunication cable shielding.
- *Individual case of lead poisoning*: Source investigations can be used for *individual* subjects, for example, to explain a single child with severe lead poisoning presenting at a local hospital. The goal, in such a case, is to identify and remove the immediate source(s) of severe lead poisoning for that individual, as well as for other family members or neighbors who might be at risk from the same source(s). Individual source investigations can also offer useful case reports about the potential for specific hazards to become a relevant source, which may also help researchers formulate hypotheses about lead poisoning sources in broader populations. (For example, traditional kohl/surma eyeliner was found to be the cause of a very severe case of lead poisoning in Belgium and may also be a relevant source for communities in which kohl/surma is commonly used.^{xxxiii}) However, the findings of a single individual source investigation are rarely generalizable beyond its specific subject.
- *Cluster of individuals or households with high BLLs*: Source assessment may be used to explain a cluster of individuals or households with unusually high BLLs. Clusters may be defined geographically, such as a group of people with elevated BLL living in the same neighborhood, sometimes called a *hotspot*. Alternatively, a cluster may be defined by other

demographic or behavioral characteristics, such as unusually high BLLs among Afghan refugees living in King County, Washington.^{xxxiv} Cluster source assessment aims to identify one or more common exposure sources among those with elevated BLLs and subsequently to remove or remediate the common risk factor. The results of such investigations may be partially generalizable (at least as indicative evidence) to individuals and families outside the specific study population who may nevertheless be known or suspected to share the common exposure source. For example, if a geographical cluster of elevated BLLs was attributed to a lead water main, the finding would most likely apply to others who also receive water from the same source. Likewise, lead-contaminated cookware was found to be a major source of lead exposure for Afghan refugees in Seattle.^{xxxv} As a result, cookware could now be considered a possible (though not definitive) suspect for high BLLs in Afghanistan and in other Afghan refugee populations.

- *Population lead exposure*: Finally, a source assessment process may be carried out to identify sources of lead exposure and their relative importance for an entire population—which could in turn be defined at different levels of aggregation, from local neighborhoods to cities, states, countries, or even (at least theoretically) supranational blocs or regions such as South Asia. As it is not possible in most cases to directly survey or take household measurements for the *entirety* of a population, such exercises usually select and study a representative sample of individuals and households, with the goal of generalizing more broadly. Potentially, sample measurements may be triangulated with population-level administrative data (e.g., on consumption patterns and infrastructure) to create a fuller picture of differing sources or intensity of exposure across different population subgroups. Because populations are diverse in both level and sources of exposure, population-level source assessment exercises must account for and explain variation among the population under investigation. By virtue of their relatively high level of generalizability, population-level source assessment exercises are likely to be highly policy-relevant, as governments can identify the most important local sources of lead exposure and subsequently counter them, for example with new regulations, enforcement actions, public awareness campaigns, and direct remediation.

2.3 Definitions and terminology

We are not aware of consensus definitions for different types of source assessment, though some specific terms have generally accepted implications. For the purposes of this paper, we distinguish the following terms for different types of source assessment, each with different objectives and their own standards of evidence, although in practice studies may not fit neatly within these boundaries:

- *Source assessment* or *source investigation*: Umbrella terms, potentially encompassing all categories described below.

- *Hazard identification* or *hazard assessment*: Indicates an effort to identify products or environmental media which have the potential to cause exposure, by detecting lead contamination using chemical analysis.⁴
- *Risk assessment*: Roughly synonymous with *source identification*, indicates an effort to demonstrate that a source has caused exposure via a human exposure pathway.⁵
- *Source apportionment*: The most evidentiarily demanding, indicates an effort to quantitatively apportion exposure in a population to different known sources (e.g., 30 percent of exposure in a population due to lead-contaminated soil and 20 percent due to lead-contaminated water).⁶

Part 3: Methods in source assessment

This section reviews the methods available for conducting source identification and apportionment. We present each method individually but note that the process of identifying potential sources and attributing exposure will generally make use of multiple methods, often in a sequential fashion.

We distinguish between the following tools used by investigators in identifying sources and attributing exposure, describing the characteristics, capabilities, and limitations of each: life-cycle, process, market, and material flow analysis; chemical analysis; biokinetic modelling; statistical approaches; experimental and quasi-experimental methods; and isotopic analysis. We then conclude the chapter with a discussion of how multiple methods are used and integrated under real-world conditions.

3.1 Life-cycle, process, market, and material flow analysis

While conceptually distinct from other methods, there are a set of related methods that can help demonstrate the potential for a particular product, activity, or industry to cause widespread

4 *Hazard assessment* or *hazard identification* are terms commonly used in many subfields of environmental health (Chartres, Nicholas, Lisa A. Bero, and Susan L. Norris. "A Review of Methods Used for Hazard Identification and Risk Assessment of Environmental Hazards." *Environment International* 123 (February 1, 2019): 231–39.

5 The US Environmental Protection Agency uses the term *risk assessment* as an umbrella term for establishing the risk posed by a particular source, as well as evaluating all risks responsible for exposure identified in some population (<https://www.epa.gov/superfund/lead-superfund-sites-risk-assessment>). Their use of the term is therefore roughly equivalent to what we term *source assessment*. We see it as important to distinguish risk assessment from hazard assessment, so we use the term *source assessment* to describe the entire process.

6 In environmental health, source apportionment is primarily used to describe the process of identifying the primary emissions sources contributing to total air pollution. With reference to lead, it has been used sporadically to describe the process of identifying the original sources of lead in environmental media (Gulson, Brian, Michael Korsch, Bruce Dickson, David Cohen, Karen Mizon, and J. Michael Davis. "Comparison of Lead Isotopes with Source Apportionment Models, Including SOM, for Air Particulates." *Science of The Total Environment* 381, no. 1 (August 1, 2007): 169–79. <https://doi.org/10.1016/j.scitotenv.2007.03.018>), but increasingly policy and research discussions have used the phrase to describe a process of quantitatively attributing exposure to different sources (Rethink Priorities. "Exposure to Lead Paint in Low- and Middle-Income Countries," March 3, 2023. <https://rethinkpriorities.org/publications/exposure-to-lead-paint-in-low-and-middle-income-countries>). This is how we use the term in this paper.

contamination and/or population exposure. This umbrella category is most informative for top-down source assessment (analyzing one or more specific sources) and can include several specific types of analysis:

- *Life-cycle analysis* follows a specific lead-containing product or industry across the entirety of its lifespan, cataloguing how the product is constructed, distributed, used, and discarded or recycled—and potentially demonstrating the opportunities for contamination or exposure at each point. For example, a life-cycle analysis of lead paint would consider occupational exposure and environmental contamination during its manufacture; direct occupational and consumer exposure during its application; exposure hazards as the paint degrades and chips over time; and risks when it is ultimately stripped, demolished, or remediated.^{xxxvi}
- *Process analysis* offers a more limited and focused analysis on a single component of the product or industry life cycle, providing detailed information about how the process works and associated risks of exposure or environmental contamination. For example, a process analysis of battery recycling in Malawi showed that remanufacturing a single lead-acid battery released 100 times the lethal oral dose of lead into the environment.^{xxxvii}
- *Market analysis* seeks to describe and explain the market for products containing lead, and therefore shed light onto the *extent* to which related pollution and exposure takes place as well as the *underlying rationale* for why contamination or pollution is occurring. For example, a project on lead-acid battery recycling in Africa found that large but substandard facilities ran the most profitable recycling operations and that these kinds of facilities would quickly take over from small-scale operations once recycling in a country had reached a certain scale.^{xxxviii} In Bangladesh, interviews with wholesalers of lead-adulterated turmeric revealed that lead chromate pigment was added during polishing to enhance the color and thus improve the marketability of poor-quality roots, without full knowledge of the harm being caused by adulteration.^{xxxix} In some cases, market analysis can demonstrate that government policies may have a role in catalyzing pollution; in Bangladesh, an extremely high tax on imported batteries discouraged the replacement of locally made, poorer quality lead-acid batteries with a short lifetime, thus incentivizing frequent recycling.^{xi}
- *Material flow analysis* quantifies the flows, stocks, and uses of materials (e.g., lead or a specific lead-containing compound or product) in a geographic area or specific process. In so doing, it can help identify where lead is used and how much lead is unaccounted for—which often means leakage into the environment or landfills. For example, a market analysis by the International Lead Association documented the industries and use cases that were generating used lead-acid batteries in Bangladesh; their analysis showed that a significant majority (76 percent) of those batteries had been used in e-rickshaws, helping to demonstrate an evolving market for lead-acid batteries away from more traditional use in gasoline-powered cars.^{xii}

3.2 Chemical analysis for lead detection

Chemical analysis refers to a suite of methods aimed at detecting the presence of lead contamination within suspected products or environmental media. Chemical analysis, on its own, may be sufficient for *hazard identification*—that is, establishing that a source *could* pose a hazard, without necessarily demonstrating that it is a current source of actual human exposure. Beyond hazard identification, chemical analysis is often a necessary (but not sufficient) input into more extensive processes of source identification and apportionment, described in sections below.

Chemical analysis can be divided into *qualitative* methods, which indicate only the presence (over some given concentration) or absence of lead; and *quantitative* methods, which measure the concentration of lead within a material or media. In some cases, qualitative and quantitative methods may be used most effectively in concert; for example, qualitative methods may be used to quickly and inexpensively screen a large area, with quantitative follow-up where high levels of lead are initially detected.

Qualitative methods

Qualitative methods for chemical analysis include the following:

- *LeadCheck™*: Previously produced by 3M™, LeadCheck swabs were a low-cost test recognized by the US Environmental Protection Agency (EPA) that detected lead on surfaces. The test involved applying a reagent to the surface, which turned red if lead was detected. However, these tests have recently been discontinued by the manufacturer, leading to supply issues.^{xiii} Similar tests are now marketed by other companies, such as the *SCITUS Know, Understand* test, but these have not yet received EPA recognition.
- *D-Lead® Paint Test*: The D-Lead Paint® Test is EPA-recognized and designed to detect lead chromate in paint coatings. The test involves scraping off a small paint sample, combining it with a reagent, and then adding a second solution. The resulting mixture will turn dark if lead is detected.
- *Lumetallix*: A relatively new testing method, Lumetallix allows for surface lead detection in many materials.^{xiii} The test combines a sprayed reagent with UV light; objects that contain lead will glow green under the UV light after they are sprayed,^{xliii} with a detection limit of 500 parts per million (ppm) for paint.^{xliii}
- *Colorimetric water tests*: There are several at-home test kits on the market which ostensibly allow users to test for lead contamination of drinking water. These include strip tests, where a test strip is lowered into the water sample, or vial-based tests, where a reagent is added directly to the water sample.^{xliii} In either case, a specific change in color indicates the presence of lead, and for some tests the extent of color change may offer a qualitative indicator of different concentrations. However, the performance of such tests is typically

problematic; most are insufficiently sensitive to detect lead in drinking water at or near the EPA action level,^{xlvii} and no colorimetric water tests are EPA-recognized.

Quantitative methods

Quantitative methods for chemical analysis include the following:

- *Laboratory methods*: There are several laboratory methods that can analyze lead concentrations in a range of media.^{xlviii} Dust is typically collected with a fiber wipe, which is then dissolved in acid and analyzed. Paint, soil, and water are typically collected directly and may be combined with a reagent before analysis, depending on the specific laboratory method used. Samples must be transported to laboratories for analysis, and the equipment can be very expensive (instruments cost US\$100,000 and more).^{xlix} For results to be reliable, laboratories must follow strict protocols to prevent contamination, potentially indicated by certification or enrollment in a laboratory proficiency program.
- *Portable XRF*: The portable x-ray fluorescence (XRF) is a relatively small, handheld device which can detect the concentration of lead (and other metals) in solid media, with very short analysis times (typically less than one minute). The accuracy and reliability of XRF measurement has increased dramatically in recent decades, such that they are often comparable to laboratory methods.^l XRF devices are relatively easy to use with minimal training, and they do not require specific laboratory expertise. However, appropriate safety training, calibration checks, documentation, and standard testing protocols are necessary to provide reliable results. These characteristics—portability, ease of use, rapid results and high accuracy—have elevated XRF devices as indispensable tools for source identification and enforcement. However, devices are still relatively expensive (US\$10,000 to \$40,000) and require periodic replacement of x-ray tubes.

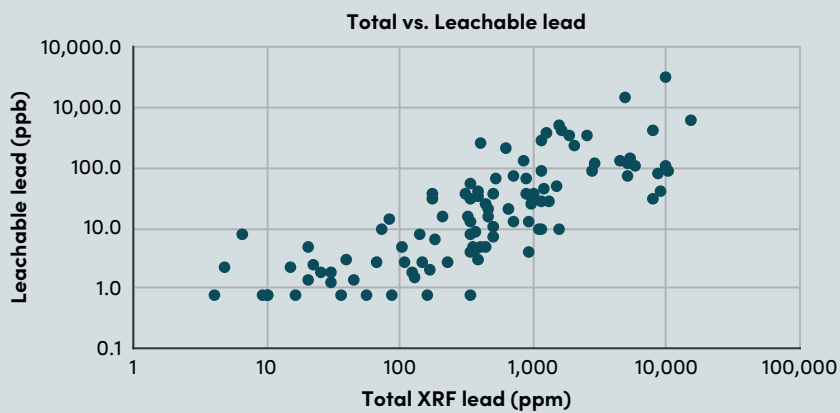
BOX 1. Leachate testing

There is growing evidence that aluminium pots and pans produced from scrap metal—which are commonly found across many LMICs—frequently contain lead.^{li} This finding leads to a critical second-order question: How much lead, if any, leaches from these contaminated pots into food and water? High rates of leaching would imply that lead-contaminated pots and pans may be a major source of global lead exposure, while low rates of leaching would imply a far smaller contribution of this potential source to the overall burden.

There is no established method for leachate testing. A preliminary study by Pure Earth tested 102 aluminium pots from 25 countries by boiling a 4 percent solution of acetic acid in the pots for two hours; researchers subsequently measured lead levels in the acetic acid solution.^{lii} This can be considered a relatively aggressive test, as standard cooking conditions are likely to be less acidic and involve less cooking time, meaning that less lead should dissolve during everyday use.

A significant number of pots leached sufficient lead to meaningfully increase BLLs (see Figure 3).^{lviii} (Indicatively, for children under age 7, 10 µg/L in leachate would roughly translate to a 0.47 µg/dL increase in BLL in children; 50 µg/L to a 2.24 µg/dL increase; and 100 µg/L to a 4.27 µg/dL increase, all assuming daily ingestion of 250 grams of food at the specified lead leachate concentration.) Lead levels in the pots themselves were moderately predictive of the amount of lead leached during cooking, with higher total lead generally resulting in higher leachable lead. The manufacturing technique, distribution of lead in the pot, and heating and tempering histories also influenced how much lead would leach.^{liv} However, pots with total lead levels below 100 ppm had only a 5 percent chance of leaching more than 10 µg/L—a relatively low reference level that would imply an increased BLL of 0.47 µg/dL in children. Based on this indicative evidence, 100 ppm total lead in an aluminium pot might be a reasonable reference level for initial hazard identification.

FIGURE 3. Relationship between lead content of pots and leached lead in acetic acid solution^{lv}



3.3 Biokinetic modelling

Biokinetic modelling is an approach to source assessment used to quantitatively model how lead in different environmental media is taken up by the body, resulting in elevated BLLs. It relies on data about the concentration of lead in various media—water, air, food, soil, and so forth—as well as assumptions about the estimated rates of intake (quantities of the media ingested or inhaled daily) and uptake (the proportion of ingested or inhaled lead entering the circulatory system). If the inputs and assumptions are accurate, biokinetic modelling allows researchers to quantitatively estimate the contribution from different sources to an individual or population’s total exposure. It also produces predicted BLLs based on model inputs, allowing for the model to be validated using actual BLLs measured in the population.

Biokinetic modelling is commonly implemented using the EPA’s Integrated Exposure Uptake Biokinetic (IEUBK) or Stochastic Human Exposure and Dose Simulation (SHEDS) models.^{lvi,lvii} Intake and consumption rates can be input by users, although the models also offer default values derived from research. The default uptake (absorption) rates used in the models typically rely on experimental studies using animals or on older studies on children.^{lviii}

Notably, default intake and uptake rates are generally calibrated to research conducted in the United States. Intake rates may differ in other settings, including LMICs, for example, if dust is more prevalent in the environment, if hand-to-mouth behavior is more common, or if dietary intake rates are different. Further research is likely needed, therefore, to tailor and validate models relevant to conditions in LMICs. Uptake rates may also differ due to differential rates of malnutrition, including iron and calcium deficiency.^{lix} However, many study designs to measure uptake rates are no longer ethically acceptable.

There are several potential use cases for biokinetic modelling vis-à-vis source identification and apportionment, depending on the information available to modellers (Table 2).

TABLE 2. Using biokinetic modelling to identify and apportion sources of lead exposure

Information Available	Information that can be Estimated from the Biokinetic Model	Indicative Example
Lead concentration in single type of environmental media	Predicted contribution of that source to BLLs in the population, in absolute terms	A lead concentration of 60 ppb in drinking water would predict a BLL of 5 µg/dL in children ages 24–36 months, suggesting it is a major source of lead exposure ⁷ ; however its relative contribution is unknown and could be very large (if local BLLs are roughly 5 µg/dL) or relatively small (if local BLLs are very high, for example, in close proximity to a battery recycling site).
Lead concentration in two or more types of environmental media	Predicted contribution of each source to BLLs in the population, in absolute terms; relative importance of each source <i>to each other</i> as potential drivers of lead exposure	If lead concentration in drinking water is 60 ppb, and lead concentration in food is 56 ppm, this would roughly predict a BLL of 7.2 µg/dL in children ages 24–36 months. Lead in drinking water would be roughly twice as large a driver of lead exposure in this population relative to lead in food.
Lead concentration in one or more types of environmental media, and BLLs in the population	Proportion of elevated BLL attributable to each of the specified sources in that population, and remaining unexplained portion of elevated BLLs in that population	If lead concentration in drinking water is 60 ppb and observed BLLs are 10 µg/dL in children ages 24–36 months, then drinking water contamination can explain roughly half of the elevated BLL seen in the population. The remainder is considered <i>unexplained</i> and likely caused by other sources.

7 All calculations made using EPA IEUBK model. <https://www.epa.gov/superfund/lead-superfund-sites-software-and-users-manuals>.

3.4 Statistical approaches

Also known as epidemiological analysis, statistical approaches involve identifying statistical associations between elevated BLLs and suspected predictors of lead exposure, potentially including age, geography, religion/ethnicity, consumption patterns, behavior, and occupation, among other factors. For example, statistical analysis could be used to investigate whether BLLs are higher, on average, in families that consume large quantities of turmeric versus those that do not. In turn, a statistical association between turmeric consumption and lead exposure could provide indicative (but not causal or conclusive) evidence that turmeric might be a suspected source of lead exposure.⁸

Potential statistical analysis designs may include simple regressions, variants of case control design,⁹ and time series analysis. While observational studies may be conducted as a purely statistical exercise—without any chemical analysis—their findings are often strengthened by also measuring for contamination of suspected sources, as well as the dose–response association between levels of contamination and exposure levels. For example, an association between turmeric consumption and BLLs is more likely to be causal if (1) chemical analysis of turmeric suggests high rates of lead contamination; and (2) the families with the highest BLLs also have the most severely contaminated turmeric in their kitchens. With sufficient sample size, statistical analysis can also provide indicative evidence about the relative importance of multiple sources.

Relatedly, geospatial modelling explores associations between hotspots of lead exposure and local characteristics such as the age of housing stock or proximate sources such as lead smelting facilities. It has been implemented successfully in the United States, where it showed moderate correlations between elevated BLL prevalence and the proximity of lead service lines.^{1x}

3.5 Experimental and quasi-experimental methods

In some situations, experimental methods, or *trials*—in which a *treatment* is offered to one group of individuals, households, or communities, but not to an equivalent *control* group—can help to shed light on whether (and to what extent) a potential source contributes to elevated BLL. For example, policymakers may suspect that contaminated aluminium pots are a substantial source of lead exposure within a given region. Researchers could investigate this hypothesis by randomly selecting some families to receive new, lead-free aluminium pots in exchange for relinquishing their old, potentially contaminated cookware. After some follow-up period, researchers could then measure whether and to what extent BLLs decreased for families receiving the intervention, compared with families who did not. If the relative drop in BLL is substantial, it would indicate (1) that replacing

8 Alternatively, the observed association could be caused by statistical confounding. For example, it is possible that local turmeric is not lead-contaminated—but it is most likely to be consumed by members of the South Asian diaspora, who are also more likely to use surma/kohl eyeliner with high lead concentrations.

9 To imitate a classic case–control study—which is not applicable as no individual is completely unexposed to lead—some studies divide a sample into those with the highest BLLs and those with the lowest. The two groups can then be compared in characteristics and behavior to identify possible drivers of high exposure.

pots may be an effective intervention, and (2) that pots are a major source of lead exposure in that study population. Depending on the study design and context, it may also be possible to infer more quantitative insights about the contribution of a given source (e.g., aluminium pots) to overall BLLs.

Experimental methods are not yet widely used for source identification and apportionment, but there is some precedent. A systematic review of papers studying the effectiveness of household interventions to prevent domestic lead exposure identified 13 randomized trials.^{lxv} Three trials on dust control interventions found limited evidence of an effect on BLLs, despite the interventions substantially reducing lead levels in household dust. This is potentially suggestive that household dust only plays a minor role in driving lead exposure in these settings. This conclusion can only be tentative, partly because there may be a lag in changes in BLLs due to remobilization of lead from the bones into circulation.^{lxvii} In a more recent study, researchers randomized the replacement of leaded water pumps with lead-free alternatives in Madagascar, finding that this intervention reduced median BLLs from 8.6 µg/dL to 6.3 µg/dL. This represents strong evidence that water pumps were an important driver of exposure in the country.^{lxviii} Experimental studies must always be evaluated and approved by an ethics board, and designs must align with ethical principles for experimental design.

In some cases, researchers can exploit *natural experiments*—situations in which there is quasi-random variation across groups and/or time due to policy changes or other external events—in lieu of setting up their own dedicated trial. For example, researchers found that flooding from Hurricane Katrina resulted in decreases in soil lead levels in New Orleans, and a simultaneous decline in children’s BLLs.^{lxix} This presents indicative evidence that lead in soil had been an important contributor to children’s lead levels in the city.

3.6 Isotopic analysis

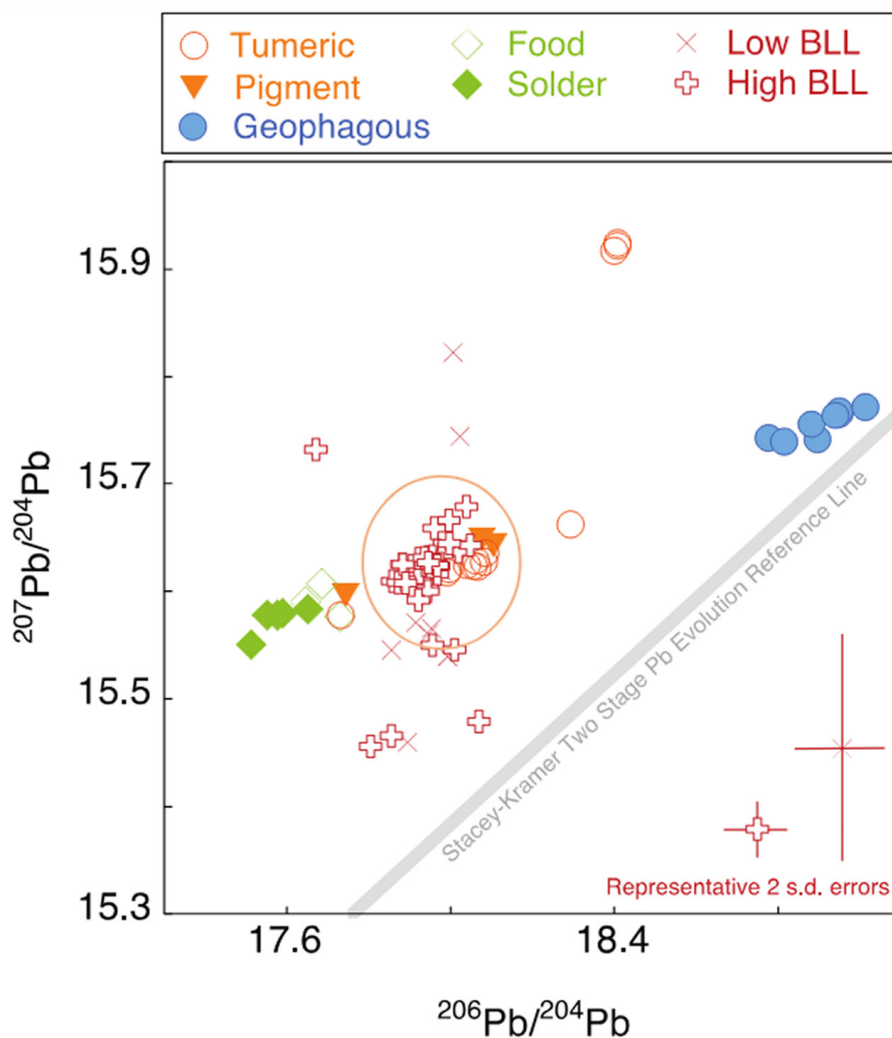
In nature, lead can take the form of four different isotopes, with each isotope defined by the number of neutrons in the nucleus. Any given sample of lead will include all four isotopes—but depending on the age of the lead, the ratio (relative proportion) of the four different isotopes will vary substantially. The isotopic ratio thus comprises a distinct, individual *fingerprint* for any specific source of lead and is generally unaffected by biological or industrial processes.^{lxx}

Isotopic analysis compares the isotopic composition of lead found in the body (blood) to the isotopic composition of potential sources. So long as the isotopic compositions of two or more sources are sufficiently distinct (which is not always the case), it is possible to use this approach to generate suggestive evidence attributing exposure to one source over the other(s).

Isotopic composition can be compared graphically, or in certain situations, applied using mixing models. In Bangladesh, for example, isotopic analysis supported the case that contaminated turmeric was the primary source of exposure in rural populations (Figure 4).^{lxxi} The graphical representation was used to map three different lead isotopes—with the ratio of ²⁰⁶Pb to ²⁰⁴Pb on the x-axis, and the

ratio of ^{207}Pb to ^{204}Pb on the y-axis. This was done both for blood samples and three suspected sources: lead solder, lead pigments in turmeric, and geophagous materials. It showed that the isotopic composition of lead pigment was by far the most closely aligned with the composition of lead in blood, strongly suggesting that turmeric was the most likely of the three studied sources to be an important contributor to population lead exposure.

FIGURE 4. Isotopic composition of BLLs in blood and three suspected sources, rural Bangladesh^{lxvii}



3.7 Integrating methods

While each method described above can offer useful information about one or more potential sources of lead exposure, source assessment is typically most powerful when multiple methods are used and integrated, helping paint a more cohesive portrait of the major contributors to lead exposure in a population.

For example,¹⁰ an investigation might begin by identifying potentially relevant sources through a review of the scientific literature, especially studies conducted on similar populations. This could also be accompanied by an anthropological investigation, involving structured or unstructured interviews with exposed individuals or households, to help to understand possible behaviors or characteristics that might have resulted in exposure. This stage could then be followed by assessing the patterns of population exposure levels, including the geographic distribution of BLLs and any spatial associations. A geographic concentration of acute cases might indicate the presence of industrial contamination, which would be somewhat corroborated if the area also included a known industrial site. Finally, hypotheses about the impact of specific sources can be tested using chemical analysis, to confirm the presence of lead in a particular product or media, or via a case–control study, to confirm the association between lead contamination and an elevated BLL.

In some circumstances, initial data collection, chemical analysis, and statistical analysis could be usefully followed up with isotopic analysis, provided that the composition of lead in competing sources is sufficiently distinct. It may also be possible to evaluate results by conducting biokinetic modelling. For example, in the Republic of Georgia, common intake rates of a spice found to be regularly contaminated by lead were calculated with online recipes and fed into the IEUBK model.^{lxviii} This returned predictions for BLLs that aligned closely with observed results, lending further credibility to the hypothesis that spices were the driving source of lead exposure.

Below, we offer a more detailed case study for how different methods were combined in rural Bangladesh to investigate multiple suspected sources and identify the major contributor(s) to elevated BLLs.

Case study: rural Bangladesh

Background: For many years prior to 2018, studies in rural districts of Bangladesh had consistently found high BLLs among children, despite the relative absence of industrial contamination.^{lxix} Earlier studies had identified several factors associated with elevated BLLs, including the use of some traditional medicines and nutritional deficiency. Chemical analysis had also confirmed the presence of lead in several foods, including rice and turmeric.

Initial study design: In 2018, 430 pregnant women were enrolled in a case–control study to gather more evidence on the drivers of high lead levels in rural Bangladesh.^{lxx} A working hypothesis was that elevated BLLs were primarily caused by lead arsenate pesticides, so the sample only included women who reported primarily consuming rice grown in their own field, and who could therefore accurately report their use of agrochemicals. Two groups were compared: 59 controls (BLLs below 2 µg/dL) and 57 cases (BLLs above 7 µg/dL).

¹⁰ Based on framework developed by Jenna Forsyth and presented at the January 24 workshop.

Initial study results: Spatial analysis demonstrated significant clustering of cases, although they were not different in proximity to roads. Analysis showed no relationship with risky occupations, use of paint, or traditional medicines, but did show that cases had higher consumption of canned food, were more likely to grind rice, and were more likely to use certain pesticides and herbicides. Chemical analysis, however, showed minimal lead contamination in pesticides and herbicides, and little evidence of contamination in the soil, water, and rice of participant’s homes. On the other hand, high levels of lead were found in the cans used to store food, caused by the practice of repairing cans with lead solder, as well as in turmeric samples. While the study was underpowered to measure an association between elevated BLLs and turmeric contamination, the presence of contamination was suggestive.

Follow-up study design: Initial results spurred a follow-up study to establish which of the remaining suspected sources—lead-soldered food cans, turmeric, and clay and ash (geophagous) tablets consumed in pregnancy (which other research had confirmed to be a potential contributor)^{lxxi}—were driving elevated BLLs in Bangladesh.^{lxxii} Forty-five individuals participated in semi-structured interviews. Where applicable, researchers also analyzed respondents’ turmeric, cans (and food stored therein), and geophagous tablets for lead concentration and isotopic composition. A laboratory experiment was also conducted to understand potential lead transfer from solder to food.

Final results: While lead concentrations in food storage cans and geophagous tablets were high, their usage was too low to explain widespread exposure. Lead levels in turmeric were lower, but their high usage as well as high bioavailability made them a more plausible factor for widespread exposure. Isotopic analysis provided further evidence for turmeric as a potentially significant factor: the isotopic composition of lead in blood, especially those with greater exposure, aligned more closely with that of lead in yellow pigment used in turmeric processing versus the lead in cans or geophagous tablets.

Policy response: In response to these findings, the government launched a nationwide intervention to end the adulteration of turmeric, which resulted in the proportion of market turmeric samples containing lead falling from 47 percent in 2019 before the intervention to 0 percent in 2021.^{lxxiii} Blood testing since then has shown that average BLLs of children dropped around 20–30 percent from 2013 to 2023, providing some evidence that turmeric was a significant, but not sole, contributor to lead exposure in rural Bangladesh.^{lxxiv}

Part 4: Priorities for source assessment research

Previous sections have provided an overview of the source assessment process, including its underlying scientific basis and specific methods within it. In this section, in turn, we consider key *global* knowledge gaps in understanding the primary sources of lead exposure and propose potential lines of research to address them.

More specifically, the questions raised below are primarily related to *top-down* research questions—that is, lines of inquiry related to the prevalence and/or impact of one or more specific sources. While not a comprehensive list, they are likely to have broad relevance across specific countries and settings; they include both foundational scientific questions (e.g., the extent of to which lead in aluminium pots will leach into food), as well as inquiries about market structure, life cycle, and prevalence of lead-contaminated goods and infrastructure.

Primary drivers of exposure will vary greatly between and within countries and over time, with different populations vulnerable to different sources of exposure. The global relevance of these *top-down* research questions, therefore, can be contrasted with local, *bottom-up* source assessment studies, which are essential for understanding any given context but have limited individual generalizability outside of the specific population studied. Individual countries themselves must build local systems for identifying the key exposure sources domestically, both now and as new sources emerge or become more prominent. In the interim, we strongly recommend increased investment in standalone *bottom-up* source assessment studies across a wide range of contexts, in addition to the thematic *top-down* research questions we consider below.

4.1 How widespread is contamination from lead-acid battery recycling?

Knowledge gap: Over 85 percent of all lead in circulation is used in lead-acid batteries,^{lxxv} and improper recycling of these batteries has been found to be a problem in LMICs across all regions.^{lxxvi} Both licensed industrial facilities and informal, small-scale operations have been shown to cause environmental contamination, at least in some settings.^{11,lxxvii} Still, the scale of this industry, and its geographic distribution, remains uncertain. Pure Earth's Toxic Sites Identification Program (TSIP) has identified pollution from over 600 lead-acid battery recycling and repair facilities,^{lxxviii} including some small-scale operations, but by their nature these are impossible to exhaustively document; a validation study in Ghana, for example, estimated that TSIP had identified less than one-seventh of total sites.^{lxxix}

Beyond the scale of recycling itself, there are also uncertainties regarding the reach of contamination from known recycling sites. It is known that improper recycling can cause substantial, often acute exposure to communities in immediate proximity of operations, as well as to workers and their families. But recycling has the potential to drive wider contamination—most directly through emissions from uncontrolled smelting, but also, potentially, through run-off of contaminated soil or human mobility (e.g., workers tracking lead from their workplaces to homes or communities).

11 Small-scale, informal battery recycling is inherently dangerous, as the scale of operations is insufficient to support proper safety equipment and precautions. It is possible to safely recycle batteries in large-scale, formal facilities, as commonly occurs in the United States, with minimal environmental contamination. However, in practice, many formal recycling facilities in LMICs have been shown to cause levels of environmental contamination comparable to those of unregulated informal operations.

Isotopic analysis has shown that submicron particles from large smelters can be deposited up to 250 kilometers away,^{lxxx} but the magnitude of exposure from this kind of highly dispersed contamination is mostly undocumented. While it is known that informal operations result in a significant proportion of lead being lost to the environment, it is still unknown how much of this loss is transferred to the air, rather than the soil; this has important implications for the magnitude of resulting exposure, as airborne lead poses a much greater immediate exposure risk.^{lxxxi} The risks posed by lead in soil, which are expected to represent the majority of lead lost in the process, are also uncertain, owing to the heterogenous dynamics of lead in soil described in section 1.2.

Potential research streams: Additional scoping work could provide further evidence about the reach of improper recycling, how important small-scale informal facilities are compared to licensed industrial smelters in driving environmental contamination, and the incentives that drive informal recycling. Material flow analyses could help illuminate the quantities of lead subject to recycling across different facility types and provide information on the end-uses of recycled material, including the types of products created and/or export destinations for recycled lead. In the long term, a more systematic TSIP could map the density and distribution of sites directly, as well as the spatial patterns of environmental lead contamination at different proximities to such sites.

An additional stream of research could seek to determine how much lead in soil and household dust may originate from lead-acid battery recycling, especially in urban settings. More life-cycle analysis studies could measure the amount of lead emissions released from different types of smelters. Researchers could also make use of isotopic analysis to attribute lead in soil to battery recycling and better understand how far lead is dispersed through these emissions. Other work could explore the dynamics of lead lost to soil in the particular contexts where recycling is now occurring (i.e., primarily urban settings in LMICs). Finally, spatial studies exploring associations between elevated BLLs and known recycling sites could be used to evaluate the extent to which such contamination leads to exposure.

4.2 To what extent are clean energy systems driving lead exposure in LMICs?

Knowledge gap: Recent research suggests that lead pollution may be an unfortunate byproduct of the rapid growth in “clean” energy systems across LMIC markets. The electric three-wheeler market in Bangladesh^{lxxxii} and the solar home system market in Malawi^{lxxxiii} have been found to be significant drivers of informal lead-acid battery recycling. In both contexts, markets are unregulated, leading to the proliferation of low-quality batteries and improper usage habits, which in turn leads to frequent breakdowns and a strong market for repairs and recycling, without adequate safety precautions. Given projections of further growth of this market in parallel with climate mitigation efforts—particularly in poorer countries where electrical grids may be limited—the scale and potential impact of this issue needs to be better understood.

Potential research streams: Additional research is needed to understand the market for and life cycle of lead-acid batteries within green energy systems and recycling chains, across different contexts. Key questions for market, process, and life-cycle analysis include the patterns of lead-acid battery usage within clean energy systems and whether this market is growing or contracting; the frequency and volume of repair and recycling required for such batteries; the physical locations and conditions under which recycling and repair take place, including the extent of localized and more distal environmental contamination; and the market incentives that drive the status quo system organization.

4.3 Are aluminium and ceramic cookware significant sources of population-level exposure?

Knowledge gap: The Rapid Market Screening program—a large-scale study of consumer products sampled from 25 LMICs—recently confirmed that lead contamination of aluminium and ceramic cookware is common across much of the developing world. In the study, 51 percent of metallic foodware items and 45 percent of ceramic foodware items had lead levels above the reference level.^{lxxxiv} Contamination of cookware was more frequent than for any other type of product sampled. However, as discussed above, there is uncertainty over the frequency and severity of exposure resulting from this contamination. Leachate tests have shown the potential for dangerous levels of leaching in pots above 100 ppm of lead (albeit with great variability). However, these tests have generally simulated quite aggressive cooking conditions, and typical cooking conditions are likely to leach proportionally less lead. There is also still limited market research on why and how contamination occurs during the production process, both for small-scale and industrial manufacturers.

Potential research streams: More research is needed to understand real-world usage patterns of both aluminium and ceramic foodware, and commensurate risks of human exposure. (For example, ceramic foodware may be more frequently used for food storage rather than for cooking, with different implications for leaching and exposure.) Other work could measure leaching of lead from both types of cookware in more typical cooking conditions in different contexts, seeking to better explain variability in leaching rates across items with similar lead content. These results could then be combined with intake rates in a biokinetic model to assess how much exposure the use of such pots might cause on a population level.

To measure the effect of contamination in pots directly, experimental studies may also be carried out: Clean pots could be randomly distributed to individuals, and their subsequent BLLs compared, to understand the impact of contaminated pots and of potential policies to prevent their use. Finally, market research is needed to understand why and how lead is introduced in the production process for metallic cookware, and therefore to inform potential interventions to reduce upstream contamination.

4.4 How dangerous are contaminated cosmetics—particularly kohl/surma eyeliner?

Knowledge gap: The Rapid Market Screening study found that 12 percent of cosmetics samples were above the reference level, with kohl (a traditional eyeliner applied to adults and children) sometimes containing extremely high levels of lead (more than 50 percent). There has been recurring debate as to how much exposure results from kohl containing lead, as it is generally in the form of lead sulphide, which has low bioavailability, and lead is less likely to be absorbed through the eye than through the lungs or gastrointestinal system. Research to address this question has included experimental studies on animals and quasi-experimental studies on children, as well as epidemiological analysis. One review of this research concluded that the risk from kohl is only theoretical,^{lxxxv} while two others concluded that there is clear evidence of kohl causing exposure.^{lxxxvi,lxxxvii} The balance of evidence suggests that cosmetics can cause exposure in individual cases. But the magnitude of this issue, and how much exposure is caused by contaminated cosmetics compared to other causes in settings where they are prevalent, is still uncertain.

Potential research streams: Experimental studies may be useful to provide definitive evidence of the extent to which cosmetics can drive exposure in a population. For example, kohl without lead could be randomly provided to families in contexts where lead kohl is common, and their BLLs subsequently compared to a control group.

4.5 How common is lead in water infrastructure in LMICs?

Knowledge gap: Lead pipes have been recognized as a potential exposure source for decades and are a leading driver of exposure in some high-income settings.^{lxxxviii} President Biden recently announced US\$3 billion to replace toxic lead pipes across the United States.^{lxxxix} Yet there has been very little research into the prevalence of lead components or solder in drinking water systems in LMICs, or the potential risk posed. One study measuring lead levels in water systems and drinking water in three countries in West Africa found lead levels in drinking water comparable to high-income countries, which would make it a comparatively minor source relative to others in LMICs.^{xc} Other research in Madagascar has identified the continued installation and use of water pumps with locally manufactured lead components in the foot valves, and a before-and-after study showed measurable decreases in BLLs of children in relevant communities once components had been replaced.^{xci}

Potential research streams: A useful starting point to address this issue would be market and life-cycle analysis of new lead pipes and components; this would help identify places where lead is still being included in new drinking water infrastructure, as well as where lead may be present in existing LMIC water systems. Further testing of water samples in LMICs, as well as a literature review of existing studies, would also be useful to understand the potential importance of this issue. Biokinetic modelling may be used to assess the contribution of existing lead levels in drinking water in LMICs to total population exposure.

4.6 How can biokinetic modelling be calibrated to LMIC conditions?

Knowledge gap: Biokinetic modelling—in particular modelling with the EPA’s IEUBK model, All Ages Lead model, and SHEDS model—has been repeatedly validated for use in the United States. Evaluations demonstrate that given measurements for environmental contamination, these models can predict expected BLLs and apportion exposure to intake of different media with a high degree of accuracy.^{xcii} However, the default parameters used for this modelling are based on research in the United States and are calibrated to these settings. A study in Central China found that the IEUBK model functioned reasonably well,^{xciii} and the model has also been successfully deployed in Georgia.^{xciv} But another validation study in Malawi found that the model performed poorly,^{xcv} demonstrating that default parameters—for intake rates of environmental media and uptake rates of ingested lead—may not generalize to many conditions in LMICs.

Potential research streams: More work should be conducted to validate the IEUBK and other biokinetic models for use in LMIC settings. To calibrate modelling to conditions in LMICs, further research may be needed on intake rates of populations in these settings. Conducting research on uptake and bioavailability rates is more challenging, as many of the study designs formerly used for this kind of research, which involved knowingly administering lead to participants, are not ethically acceptable. However, research using animal models, or reexamination of data from older studies, may be used to assess how common conditions in LMICs—including undernutrition and nutrition deficiency—may affect uptake rates.

Conclusion

This paper has reviewed research methods to identify the sources responsible for lead exposure—particularly in LMICs, where exposure is highest. In Part 1, we described the processes by which humans can become exposed to lead, including how lead enters and interacts with the human-facing environment, and the dynamics by which environmental lead is absorbed by the human body. Part 2 offered a framework for understanding the different types of research under the *source assessment* umbrella, while Part 3 reviewed the range of methods available to identify and attribute sources. Finally, Part 4 outlined knowledge gaps in understanding the primary sources of exposure globally, suggesting several top-down research streams with broad international relevance.

Overall, we find that source assessment for lead exposure is a highly developed field of research, with no shortage of methods available to investigators. A small caveat is that many of these methods have been developed in high-income countries—particular the United States—and are most relevant and accurate in those settings. There remains work to be done in calibrating certain methods to conditions in LMICs, especially for biokinetic modelling, and in identifying the most appropriate methods for use in different contexts. And while some traditional approaches to lead detection can be costly—particularly laboratory methods to measure lead in environmental media and household products—they may be augmented by the growing array of affordable, qualitative tools for lead detection.

Our findings suggest that existing methods can be deployed successfully in most LMIC settings, and there is simply a need for greater investment in such research at the national and local levels. We believe this investment is likely to be highly cost-effective in many cases. For example, work conducted to understand the sources of lead exposure in rural Bangladesh by Jenna Forsyth and colleagues between 2018 and 2019 has been estimated to have cost around US\$250,000.^{xvii} But by identifying a highly tractable source (adulterated turmeric) and the point of contamination (polishing), this work can be credited with helping to remove a significant source of lead exposure from the market, and possibly the moderate decline in BLLs in the country since 2013. It should be noted that this work was somewhat atypical in its policy impact, and costs for this type of fieldwork are likely to be higher in urban settings and due to recent inflation.

The bulk of source assessment research must be *bottom-up* research assessing exposure in a specific population, with limited applicability to other settings. However, the significant overlaps in the profiles of sources affecting different countries presents several *top-down* knowledge gaps with relevance to source assessment globally and research opportunities to inform global efforts to address lead poisoning. In Part 4, we outlined several of these questions, but others may yet emerge as the broader evidence base develops.

Finally, it is important to note that a precise understanding of the contribution of a particular source to population exposure is not always necessary to take action against it. Many interventions to mitigate lead exposure, especially regulations on uses of lead where clear alternatives exist, are highly affordable and without significant drawbacks. This is true of regulations to ban the use of lead chromate pigments in paint, for example, as affordable and equally effective alternatives are available. In such cases, it is justified to implement these interventions without clear evidence that the targeted source is responsible for significant population exposure. In turn, source assessment is more pivotal where interventions have greater direct costs (e.g., site remediation); where the intervention to ameliorate lead exposure is not obvious, such as with lead-contaminated cookware; or in cases where there is relative scarcity of affordable or equally cost-effective alternatives (e.g., recycling of lead-acid batteries). Prioritization and conceptualization of source assessment exercises thus requires investigator discretion and a clear theory of change for how source assessment will meaningfully inform policy action.

Appendix: Agenda for technical roundtable on source apportionment



Source Apportionment and Identification of Lead Exposure

Technical Roundtable

WEDNESDAY JANUARY 24, 2024

3PM–6PM GMT

Background

One of the biggest missing pieces in efforts against global lead poisoning is an adequate understanding of what is causing exposure. Since the phase-out of leaded petrol, a still increasing number of industries and consumer products have been identified as sources of lead exposure, several of which could be quite important on a global scale. But there is large uncertainty around even the approximate contribution each source makes to the overall burden globally, or to that of all but a few countries or regions.

In the same period, there has been growth in experimentation with novel approaches to assessing the contribution of different exposure sources: notably isotopic analysis, which compares the composition of lead in the body to that in potential sources. Newly identified sources, such as scrap metal pans containing lead, have raised further questions about the conditions under which exposure hazards can become risks.

There is a need for research which can calibrate existing methods of source apportionment, identify new approaches, or understand how to establish systems for source apportionment long-term, particularly in resource-constrained settings. And of more immediate relevance, there is a need to synthesise what evidence we have at present, to inform the prioritisation of ongoing efforts against lead poisoning.

Objectives

The Center for Global Development will convene a half-day technical roundtable on source apportionment of lead exposure, to feed into our broader work defining a research agenda to inform efforts to mitigate lead poisoning.

The objectives of the roundtable are as follows:

- To review the state-of-the-science on methods for source identification and apportionment, including their applications and limitations in different settings;
- To identify opportunities for further calibration of these methods, or the development of novel approaches;
- To consider where and what kind of source apportionment research should be prioritised;

These discussions will inform the development of a CGD-published policy note, which will summarise our own assessment of these issues.

Roundtable participants

Name	Title and Affiliation
Rachel Bonnifield	Senior Policy Fellow, Global Health Policy, Center for Global Development (CGD)
Anouk Amzel	Medical Officer, U.S. Agency for International Development (USAID)
Angela Bandemehr	Senior International Environmental Program Manager, Office of Global Affairs and Policy, Office of International and Tribal Affairs, U.S. Environmental Protection Agency (EPA)
Gordon Binkhorst	Senior Technical Advisor, Pure Earth
Malia Boggs	Senior Technical Adviser for Child Health, Office of Maternal, Child Health & Nutrition, USAID
Mary Jean Brown	Professor, Social and Behavioural Sciences, Harvard T.H. Chan School of Public Health
James Brown	Senior Health Scientist, US Environmental Protection Agency
Jack Caravanos	Clinical Professor of Global Environmental Public Health, School of Public Health, New York University (NYU)
Lucia Coulter	Co-Founder, Lead Exposure Elimination Project (LEEP)
Lee Crawford	Research Fellow, Education, CGD
Bret Ericson	Professor, Environmental Health Sciences, New York University School of Global Public Health
Jenna Forsyth	Academic Program Professional, Medicine—Med/Infectious Diseases, Woods Institute of the Environment, Stanford University
Richard Fuller	CEO & Founder, Pure Earth; chair of board, Global Alliance on Health and Pollution (GAHP)
Apala Guhathakurta	Public Health, Bloomberg Philanthropies
Santosh Harish	Program Officer, Global Public Health Policy, Open Philanthropy
Jessica Harrison Fullerton	Director, Global Development Incubator
Paromita Hore	Director, Environmental Exposure Assessment and Education, New York City Department of Health and Mental Hygiene
Howard Hu	Flora L. Thornton Chair of the Department of Population and Public Health Sciences, Keck School of Medicine, University of Southern California
Bruce Lanphear	Professor of Health Sciences, Simon Fraser University
Jessica Leighton	Public Health team, Bloomberg Philanthropies
Karen Levy	Co-Founder, Fit for Purpose
Maria Paola Lia	Executive Director, Global Alliance on Health and Pollution
Angela Mathee	Chief Specialist Scientist, SAMRC Environment & Health Research Unit
Drew McCartor	Executive Director, Pure Earth
Desiree Raquel Narvaez	Environmental Health Specialist, UNICEF
Willem Noorduyn	Professor, Van't Hoff Institute for Molecular Sciences, University of Amsterdam
Lucile Okio	Senior Program Manager, Global Alliance on Health and Pollution
Ellie Rodgers	Operations Manager, Fit for Purpose
Ernesto Sanchez-Triana	Global Lead for Pollution Management and Circular Economy, World Bank

(Continued)

Name	Title and Affiliation
Gabriel Sanchez Ibarra	Vice-President of Programs, Pure Earth
Justin Sandefur	Co-Director of Education Programme and Senior Fellow, GCD
Ben Savonen	Senior Associate, Global Development Incubator
Valerie Zartarian	Senior Scientist and Advisor, Center for Public Health and Environmental Assessment (CPHEA), Office of Research and Development (ORD), US Environmental Protection Agency (EPA)

Agenda

3:00–3:10 GMT	Welcome, Motivation, and Participant Introductions <i>Facilitated by Rachel Bonnifield</i>
3:10–3:40 GMT	Detecting Lead in Environmental Media <i>Presentations followed by group discussion</i> <hr/> <i>Technologies for Detecting Lead</i> —Jack Caravanos, Clinical Professor of Global Environmental Public Health, School of Public Health, New York University (NYU) <hr/> <i>Luminescent Lead Detection for Environmental Screening</i> —Willem L. Noorduin, Professor, Van't Hoff Institute for Molecular Sciences, University of Amsterdam <hr/> Objective: Build understanding around established and emerging methods for measuring lead contamination in products and environmental media.
3:40–4:20 GMT	Mechanistic Approaches to Source Apportionment <i>Presentations followed by group discussion</i> <hr/> <i>Understanding the Leachability of Lead from Aluminum Pots</i> —Dr. Gordon Binkhorst, Senior Technical Advisor, Pure Earth <hr/> <i>Biokinetic Modelling and Bioavailability</i> —James Brown, Senior Health Scientist, US Environmental Protection Agency <hr/> <i>Isotopic Analysis</i> —Jenna Forsyth, Academic Program Professional, Medicine—Med/Infectious Diseases, Woods Institute of the Environment, Stanford University <hr/> Objective: Build understanding around methods which study the mechanisms for how sources might cause exposure.
4:20–4:30 GMT	Break
4:30–5:00 GMT	Statistical Approaches to Source Apportionment <i>Presentations followed by group discussion</i> <hr/> <i>Probabilistic Modeling and Geospatial Approaches to Lead Source Apportionment: Examples of US Experience</i> —Valerie Zartarian, Senior Scientist and Advisor, Center for Public Health and Environmental Assessment (CPHEA), Office of Research and Development (ORD), US Environmental Protection Agency (EPA) <hr/> <i>Econometric Approaches to Source Apportionment</i> —Lee Crawford, Research Fellow, CGD <hr/> Objective: Build understanding around statistical methods which identify and/or quantify sources or population exposure.
5:00–5:55 GMT	Source Apportionment in practice <i>Presentations followed by group discussion</i> <hr/> <i>Synthesising Evidence from Different Methods</i> —Jenna Forsyth, Academic Program Professional, Medicine—Med/Infectious Diseases, Woods Institute of the Environment, Stanford University <hr/> <i>Lessons from Source Apportionment Case Studies</i> —Bret Ericson, Professor, Environmental Health Sciences, New York University School of Global Public Health <hr/> <i>Source Apportionment in the Field</i> —Mary Jean Brown, Professor, Social and Behavioural Sciences, Harvard T.H. Chan School of Public Health <hr/> <i>Pure Earth's Approach to Home-Based Source Assessment</i> —Gabriel Sanchez Ibarra, Vice President of Programs, Pure Earth <hr/> Objective: To share personal experiences of source apportionment in practice, in order to better understand how different evidence from different methods can be synthesised.
5:55–6:00 GMT	Wrap-up <i>Rachel Bonnifield</i>

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