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Howard W. Mielke, PhD, John A. McLachlan, PhD, Aubrey E. Schachter, MS, Andrew D. Gailey, MS, Sara P. Egendorf, MS, Ruth A. Etzel, MD, PhD

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Quantifying soil contamination and identifying interventions to limit health risks
Andrew D. Gailey, MS, Aubrey E. Schachter, MS, Sara P. Egendorf, MS, and Howard W. Mielke, PhD

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Foreword: The Impact of Soil on Children's Health: A Dirty Story

Children love to play in the dirt. When that dirt is contaminated, children can be exposed to toxic substances that may make them ill. The average child puts about 50 mg of soil and 60 mg of dust into his mouth in a typical day.[1] Children with pica, however, may ingest much more dirt. For reasons that are not yet understood, pica appears to be on the increase in the United States. An analysis by the Agency for Healthcare Research and Quality[2] found that between 1999 and 2009 the number of hospitalizations for pica among Americans of all ages almost doubled from 964 to 1862, respectively. In 2009, 31 percent of childhood pica cases were found among autistic children.

Even children who do not have pica can suffer serious harm from ingesting contaminated dirt. In 2007 and 2008 in Dakar, Senegal, 18 children died from lead poisoning that occurred because their parents were engaged in home recycling of lead-acid batteries.[3] They stored the lead-contaminated soil in their homes and their children's normal hand-to-mouth and object-to-mouth activities exposed them to fatal amounts of lead. In northern Nigeria in 2010 $>$ 200 children died from lead poisoning in villages where ore was mechanically ground as part of informal gold-mining activities.[4,5] The grinding dispersed lead widely in the villages and contaminated the soil, children's toys and eating utensils, resulting in an epidemic of lead poisoning that affected thousands of people.

In this issue, Professors Howard Mielke and John McLachlan from the Department of Pharmacology at Tulane University School of Medicine in New Orleans provide an overview of how environmental signaling works.[6] The three articles that follow were written by Aubrey Schacter, Sara Perl Egendorf and Andrew Gailey.[7–9] Ms. Schacter and Mr. Gailey obtained their master's degrees in pharmacology at the Tulane University School of Medicine and are pursuing medical degrees at Louisiana State University Health Science Center and the University of North Carolina School of Medicine, respectively. Ms. Egendorf is a Ph.D. student at the Advanced Science Research Center at the Graduate Center and at Brooklyn College of the City University of New York. Their work provides up-to-date information about the impact of lead and other soil contaminants on children's health.

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Associate Editor

Air, water, soil and environmental signaling

Howard W. Mielke, PhD,* and John A. McLachlan, PhD

Within a remarkably short timespan the world population doubled and transitioned from an agrarian to an urban-industrial society. The transition was accompanied by the major expansion of industries that releases enormous amounts of toxicants into the air, water, and soil. Naturally occurring and synthetic chemicals compounds utilized the same signaling system as vertebrate internal cell signaling systems. The concept of environmental signals provides insights to address the impact of biochemically active toxicants on humans and the ecosystems that they share with other species. Disruption of the broad signaling systems has the potential for global change that transcends the biological systems of all organisms, including humans.

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Introduction

The concept of environmental signaling arose from the observations that many environmental chemicals, including synthetic compounds and naturally occurring chemicals utilized the same signaling system as the natural hormone, estrogen. It was further observed that the signaling system was common to virtually all vertebrates. More recently, environmental chemicals including lead and other stressors have been shown to coopt endogenous signaling systems.[1]

The terms toxins and toxicants are used to distinguish natural and human sources of toxic substances. Toxins are natural products such as poisonous mushrooms, snake venom, exudates from plant leaves and roots, and soil bacteria that can be deleterious to health. The term toxicant refers to artificial products introduced by human activity into air, water, and soil. Examples of toxicants include commercial manufactured goods and industrial waste byproducts such as the metal lead, and the plethora of pesticides created to kill insects and unwanted weeds in industrial-agriculture systems. Toxicants are generally dispersed into the air and water and then globally distributed in soil and water. Environmental signaling comprehends both toxins and toxicants. By considering environmental signaling, attempts are made to find treatments of common health issues through improving environmental chemistry and preventing exposure in the first place.

> ***"From an environmental stewardship perspective, the evolving concept of environmental signals can provide insights with which to address the impact of hormonally active chemicals on humans and the ecosystems that they share with other species. Disruption of this apparently broad communication system has the potential for global change that transcends the endocrine system."[1]***

The current problems of pediatric and adolescent health occur in the context of the cultural and dynamic changes in the air, water, and soils on our planet. One of the most formidable changes is the rapid growth of the human population. Within a remarkably short timespan the world population doubled and transitioned from an agrarian era, when most of the population lived on the land, into an urban-industrial era. More than half of the global population currently live in cities.[2] The transition was accompanied by the major expansion of industry and commercial enterprises that released massive amounts of toxicants into the air, water, and soil.

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Lead (Pb) is an example of an excessively exploited naturally occurring toxic element that was converted into a widespread and debilitating toxicant. Lead is an excellent model for understanding environmental signaling. In nature Pb is found only in minute amounts and exposures are usually small. As part of industry and commerce, Pb was mined, smelted, and distributed in massive quantities and dispersed into the environment. As a toxicant, Pb contaminated the air and, as a dust, dispersed globally in soil and water.

Exposure to Pb has been associated with long-term health damage for centuries; although neurotoxic to both adults and children, the developing nervous system is known to be especially sensitive to persistent damage from short Pb exposures. Furthermore, Pb mimics calcium (Ca) and is readily absorbed in its place. Calcium is required for signaling across neuron synapses. If Pb is in the synapse instead of Ca, then nerve transmission signals are blocked, and the neurons become weakened and die. In this way environmental signals from exposure to Pb have dire consequences to individuals and society at large.[3–5]

Another example of environmental signals is represented by a class of chemicals that mimic components of the endocrine system called endocrine disrupting chemicals (EDCs). These can be synthetic organic pollutants such as the pesticide dichlorodiphenyltrichloroethane (DDT), industrial byproducts such as polychlorinated biphenyls (PCBs), or plastic constituents such as bisphenol A (BPA) that all remarkably mimic the action of the female sex hormone estrogen. Humans and virtually all other vertebrate forms of life respond to these chemicals as if they were being treated with a hormone that alters sex and sexual development.[1] The responses by vertebrates potentially disrupt natural processes and ecosystem functioning.

There are numerous examples of toxicants that were emitted in large amounts into the air, water, and soil. Many toxicants have been emitted in the environment only to later find that the toxicant causes persistent health issues in human and biological systems.[6–8] In many cases, early warnings went unheeded, research was manipulated, powerful conflicts of interests prevented action, and precautions were not exercised for stable toxicants; in the case of certain stable compounds, the hazard arises from bioaccumulation of toxicants in the food chain with devasting consequences for humans and ecosystems alike.[9]

The concept of environmental signals provides insights to address the impact of biochemically active toxicants on humans and the ecosystems that they share with other species. Disruption of the apparently broad communication systems has the potential for global change that transcends the biological systems of all organisms, including humans.[1]

Declaration of competing interest

None of the authors have any conflicts of interest to disclose.

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Mechanisms of children's soil exposure

Aubrey E. Schachter, MS,[a] Andrew Gailey, MS,[b] Sara Perl Egendorf, MS,[c] and Howard W. Mielke, PhD[d,*]

Pollution is a concerning and highly studied area, especially in the arena of children's health. The focus of this concern, however, is typically limited to air and water pollution, leaving an important source under-studied and out of the concern of the general public. Soil pollution provides a unique threat to children's health, due to their increased exposure and susceptibility to its contaminants. The microbiome of a child is developed prior to birth and continues to evolve over their lifetime with each encounter to the outside world. The environment a child inhabits directly affects their microbiome and their overall health, and through interactions with contaminated soil, a child can accumulate adverse health outcomes. The aim of this article is to summarize the methods by which soil becomes contaminated and how children become exposed to the resulting toxicants.

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Introduction

The influence of soil toxicants on children is not widely recognized or studied. Current efforts tend to focus on water and air pollution, with an emphasis on providing clean drinking water and eliminating harmful air emissions. Compared to adults children have a characteristic set of behavioral patterns and physiologic requirements that makes them uniquely susceptible to soil pollution. These risk factors increase the likelihood of encountering soil contaminants and their associated negative sequelae. This work discusses the contents of the soil including the microbiome, mechanisms of soil contamination, and mechanisms of soil exposure for children.

Microbiome

Microorganisms exert fundamental influences on all the Earth's plants and animals.[1] The study of human biology typically focuses on genes unique to human cells. However, human cells account for only about 10% of the DNA associated with human biology. Although humans inherit about 20,000 - 25,000 genes from their parents, microbiota living in the intestines alone contain about 3.3 million genes.[2] When studying human biology, it may be more appropriate to directly address the microbiome, which is a collective system of human cells and their associated microbiota. These entities function together, and each body site can be considered as a unique part of systems biology because different sites have distinctive microbiota.[2] Children interface frequently with the environment and these interactions influence and shape their microbiome. Under certain conditions, microorganisms can cause illness, but the new understanding is that most are harmless.[3] In fact microbial species help digestion, appetite management, and immune system regulation.[2]

Microbiota dominate the Earth's habitats and organisms.

Although soil microbiota and pollutants differ greatly worldwide, their direct influences on children's health are universal.[3] Exposure to the microbial world begins in utero.[4] Microbiome exposure increases as the fetus passes through the vaginal canal at birth. From birth onward, the microbiome is constantly shaped and changed by a child's exposures, with sources including inhalation, hand-to-mouth behavior, and dermal interactions.[5] Adults do mouth

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some objects and ingest vegetables grown in soil. However, adults are less likely to directly encounter soil, and have a limited risk of ingesting microbes and confronting the toxins and toxicants currently found in soil. Furthermore, adults are more capable of eliminating toxicants and pathogens because of their more mature immune and body systems.

In 1993 a National Academy of Sciences committee identified four fundamental attributes that contribute to children's increased susceptibility to toxic chemicals when compared to adults.[6] First, children have greater intake kilogram-for-kilogram of food, water, and air as well as increased exploratory behaviors that bring them into direct contact with interior dust and soil. Children also have immature metabolic pathways and are less able to excrete or detoxify toxic compounds. Children undergo rapid growth and development, and these cellular processes are affected by exposures to toxic compounds. Lastly, children have more future years of life compared to adults, which can result in a more substantial impact when accounting for overall time spent affected by the exposure.[6] Soil is a medium that particularly affects children's health. Although many interactions and exposures to soil can be beneficial, children are more vulnerable when encountering toxicants and pathogens.

Children have increased susceptibility to toxicants in soil compared with adults.

Toxicants persist longer in soil than in air and water.

Contamination

Soil pollution or contamination refers to the presence of a chemical or substance out of place and/or present at higher than normal concentrations that adversely affect a non-targeted organism.[7] Knox et al. refer to soil contamination as "soil whose chemical state deviates from the normal composition but does not have a detrimental effect on organisms".[8] Kabata-Pendias makes the delineation between contamination and pollution. Pollution occurs when an element or a substance is present in greater than natural (background) concentrations as a result of human activity and has a net detrimental effect on the environment and its components.[9] Thus, from a plant, animal, and human health perspective, soils are not considered polluted unless a threshold concentration exists that begins to affect biological processes.[9] Determining a "threshold of exposure" of a toxicant or toxin is a scientific conundrum because it requires more knowledge about metabolism and processes than is ordinarily available. For example, consider the evolving threshold of lead exposure measured in blood samples recognized as safe for children. In the 1960s, 60 μg/dL was considered safe. By 2012 no known threshold of lead exposure was recognized as safe for children.[10]

These broad definitions reflect the variety of contaminants present in soil and are indicative of the extensive effects that human-made materials exert on soil quality. A sample of common soil contaminants with negative effects on health are shown in Table 1.

TABLE 1. List of toxicants being dispersed by humanity into the air, water, and soil of the Earth.

- Metals
- Organic pesticides (herbicides & insecticides)
- Petroleum hydrocarbons
- Polycyclic aromatic hydrocarbons
- Per- and polyfluoroalkyl substances (PFAS)
- Seepage from landfills
- Seepage from solid waste dumps
- Solvents
- Tar, coal, coal ash
- Vehicle related residues along roadways
- Building material residues
- Smelting and residues
- Fertilizer by-products
- Warfare production and by-products
- Medical and pharmaceutical waste

The sampled list in Table 1 illustrates the pervasiveness of toxicants that end up in soil, and sheds light on the extensive range of commercial activities that affects soil quality. The sources of soil contamination are varied and modulate the resulting health effects. The amount, duration, and concentration of toxicants, along with many other host factors, influence how an exposed child will respond, which renders outcome prediction an extremely difficult task.

Soils can become contaminated in many ways, either from non-site or site sources.[11] Non-site sources of soil contamination include volcanic eruption or industrial emissions of aerosols that enter long-distance atmospheric transport and deposition. Other non-site sources include parent materials, horticulture or agricultural runoff, and hazardous landfill wastes that can be flushed downstream by river systems. Linear contamination of aerosols by road traffic is also regarded as a non-site source. Site contamination results from local industry, peeling paint, fertilizer, sewage sludge application, and pesticides. Specific urban site contamination sources arise at abandoned industrial sites, accident or spill sites, and waste deposit sites.

Contaminants in soil tend to persist for much longer periods of time than in the air and water compartments of the biosphere. Contamination of soil, especially by trace metals, appears to be virtually permanent according to human time scales, although concentrations may slowly decrease by leaching, plant uptake, erosion, or deflation.[9] The residence time for metals varies with depth of the soil horizon under consideration. In the top 20 cm of the soil horizon, the residence time appears to be centuries, while in the topsoil 2.5 cm of the horizon, the residence time appears to be decades.[12]

The metals of major concern in urban soils are arsenic (As), barium (Ba), cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), mercury (Hg), nickel (Ni), and zinc (Zn).[11,13] Although all of these are naturally occurring elements in rocks and minerals, each of them has been concentrated through various smelting, industrial activities, and manufacturing processes that leave traces in urban soil. Each metal behaves differently and may be found in a variety of compounds in soil.

In addition to inorganic metal contaminants, organic contaminants are also found in soil. Some of these potentially hazardous toxicants include dioxins, furans, polychlorinated biphenyls (PCBs), hydrocarbons, pesticides, and volatile organic compounds (VOCs). PCBs, benzene, and polycyclic aromatic hydrocarbons (PAHs) are among the top ten priority hazardous substances listed by the Agency for Toxic Substances and Disease Registry (ATSDR).[14]

Certain types of geologic formations can contribute high concentrations of elements such as Cr, Cu, and Ni.[15] Underground pipes can contribute compounds of ammonia, boron, sulfate, chloride, phosphorus and trace metals.[8] Dusts can contribute many metals of concern such as Cd, Cu, Pb, and Zn,[15,16] as well as PAHs and PCBs.[17] Vehicle emissions, particularly from diesel fuels, include benzene and PAHs and metals such as platinum and rhodium.[14]

While each of these contaminants may present particular environmental and human health issues, lead is one substance that has received particular attention, and because of its toxicity, will be discussed here at length. Lead is the 38th most abundant mineral in Earth's crust, and exists in crustal rocks with an average concentration of approximately 20 parts per million (ppm)[18] and in various rock types with an average of approximately 3 to 40 ppm.[19] It is dense, malleable, has a low melting point, and is easy to use for a variety of purposes. It has been mined for at least 8,000 years[20] and has been used in virtually all aspects of manufacturing and industry, including pipes, the printing press, bullets, paint, gasoline, and numerous 'green' technologies such as hybrid batteries.[21] Even though the negative health impacts of exposure to this material have been noted for at least 2,000 years[22] and numerous researchers have documented such impacts for decades[23,24] hundreds of thousands to millions of lives have been altered during the long battles to regulate the commercial use of this element.[25,26] Because of its pervasive presence in environmental media and pernicious impacts on human health, lead serves as a key indicator for soil contamination Fig. 1.

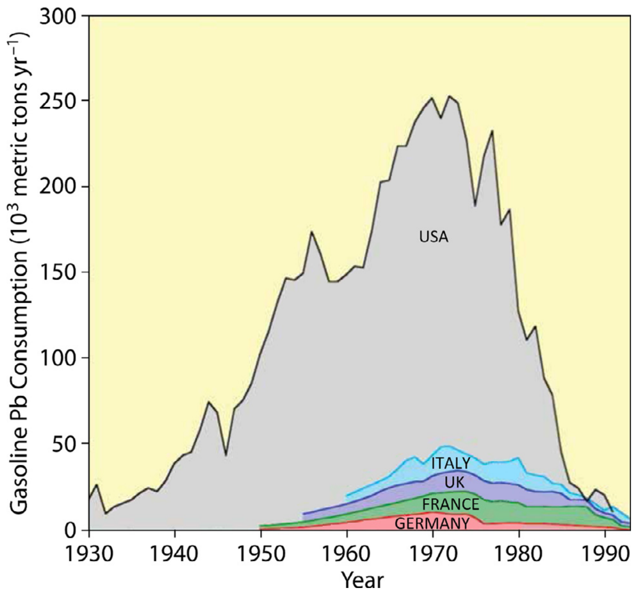

Fig. 1. Gasoline lead consumption in the USA, Germany, France, United Kingdom, and Italy from 1930 through 1993. Associated with vehicle traffic and highway development, the USA consumption was massive compared with the leaded gasoline consumption by the four European countries. Figure Credit: Boyle EA et al. 2014. Anthropogenic lead emissions in the ocean: The evolving global experiment. *Oceanography* 27(1): p.70, Fig.1. http://dx.doi.org/10.5670/oceanog.2014.10. https://creativecommons.org/licenses/by/4.0/. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 2. Photo of the flames and lead-dust contaminated smoke emitted from the burning roof at Notre Dame Cathedral on April 15, 2019. Lead dust from the burning roof contaminated communities of Paris surrounding Notre Dame. Photo credit: Milliped, Wikimedia creative commons, Notre Dame on fire 15042019–1 (cropped).jpg. https://creativecommons.org/licenses/by/4.0/. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

From the 1920s to 1986, large quantities of tetramethyl and tetraethyl Pb were added to gasoline. By January 1, 1986 when leaded gasoline was rapidly phased out in the U.S., 5 to 6 million metric tons of Pb had been used as an additive, and approximately 75% of this Pb had been emitted into the atmosphere.[27] Thus, an estimated 4 to 5 million tons of Pb had been released into the U.S. environment as a result of gasoline emissions.[27] Soil Pb has also been shown to be proportional to highway traffic flow, resulting in differential deposition depending on city size and within an inner city versus outlying community location.[28–30] In New Orleans, Louisiana, an estimated 900 tons of lead were released by vehicle exhaust during the six decades of commercially available leaded gasoline use.[29–31]

Soil pollution must be evaluated when assessing children's health.

A contemporary lead air pollution event occurred in Paris on April 15–16, 2019. The devastating fire at the Notre Dame Cathedral in Paris released over 460 tons of lead into the environment. The lead dust from the fire was deposited on surrounding soils of Paris. Levels of lead dust near the site were up to 1,117 mg/m^2 (120,774 μg/ft^{2}) – 1,300 times higher than French safety guidelines (Fig. 2).[32]

Soil contamination is intimately linked to both air and water pollution. Unlike the visual images of smog hovering over a busy city or dirty sewage water contaminating a freshwater source, however, soil pollution is totally invisible and easily overlooked.[33] Contamination of air and water sources are addressed in the Clean Air Act and Clean Water Act, and commonly receive intense and sustained attention from the media. For example, the consequences from the Flint water crisis, first recognized in 2015, continue to be regularly covered by the press in 2019.[34] Few would argue that attention to lead in water is unwarranted or unnecessary, however, lead contamination of soil has not received even a fraction of this consideration. Soil is a source of contaminant exposure that must be evaluated when assessing environmental conditions and children's health.

Exposures

There are numerous ways in which children are exposed to soil contaminants. Fig. 3 illustrates several common pathways.[35] Children have a natural curiosity and they acquire knowledge through play interaction with their environment. They gather information in many ways, including smelling, touching, and mouthing (Fig. 3). There are two major exposure pathways for human exposure to contaminated soil.[35]

Inhalation

The inhalation route of exposure is represented by the top right of Fig. 3. Particle size determines the fate and transfer of various sized particles. Soil is a reservoir for aerosol particles. After initially becoming airborne, particles are eventually washed out or deposited on the ground and, during dry climate conditions (late summer and early fall), the particles can be resuspended.[37]

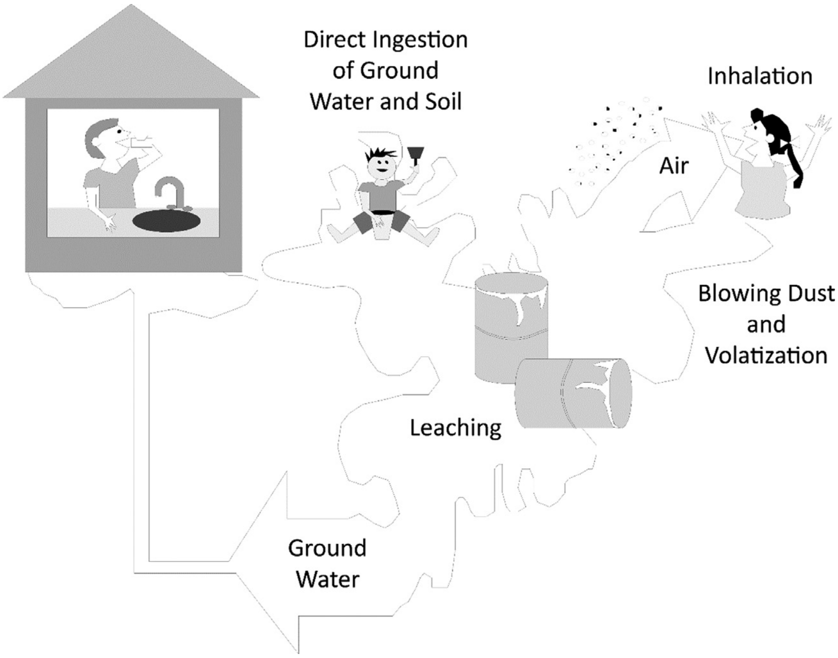

Fig. 3. US EPA illustration of major exposure pathways of air, water, and soil exposure. Credit: U.S. EPA. *Soil Screening Guidance: User's Guide*, Second Edition. EPA/540/R-96/018. July 1996 http://www.epa.gov/superfund/resources/soil/ssg496.pdf. https://creativecommons.org/licenses/by/4.0/.

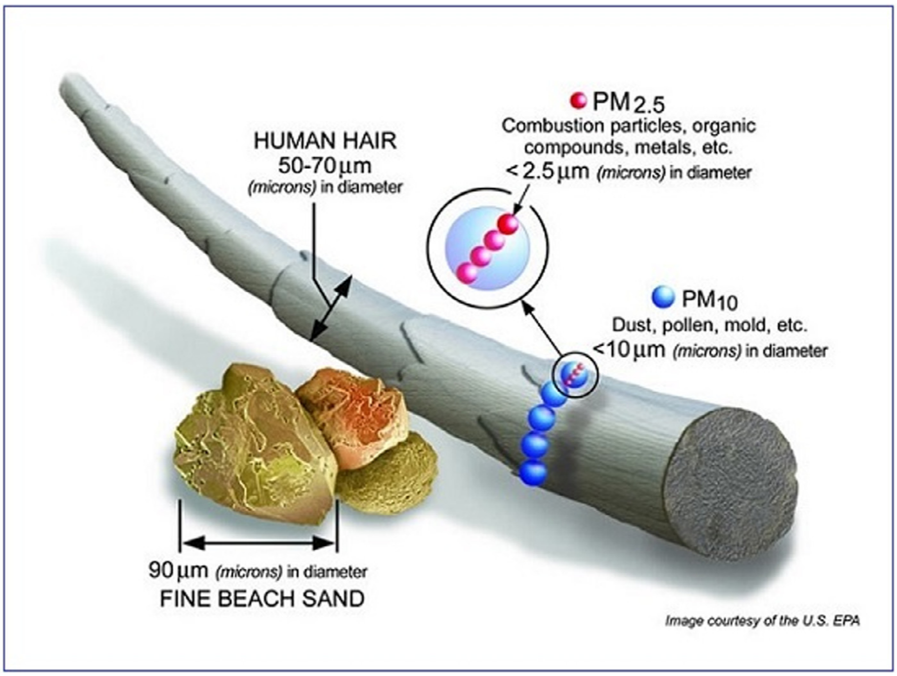

Fig. 4. Particle size determines the fate and transfer of toxicants. Combustion particles < 2.5 μm pass through the cell walls of alveoli and enter the circulatory system. Credit: US EPA. https://creativecommons.org/licenses/by/4.0/. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 4 shows the relationship of particle sizes of $PM_{2.5}$ and PM_{10} to each other in comparison with a human hair. Combustion creates the smallest, and often invisible, particle sizes.

Most of the human population now lives in cities, and air pollution is a threat to the health of urban dwellers.[33] Inhalation exposes all people; however, children are especially vulnerable to the hazards of airborne dusts.[36] Studies examining inhalational exposure in children focus on measuring inhalation rates in comparison to adults. Children have a higher resting metabolic rate and oxygen consumption rate than adults. The oxygen consumption rate of a child between 1 week and 1 year of age is 7 mL/kg/minute, while the rate for an adult is 3–5 mL/kg/minute.[36] This places oxygen consumption for infants at nearly double that of adults, increasing their exposure to hazardous dusts. The U.S. Environmental Protection Agency (EPA) suggests that the recommended daily inhalation rates of hazardous dusts are less than or equal to 4.5 m^3/day for infants, with incremental increases tolerated with age, resulting in up to 10 m^3/day in 6–8-year-olds. At age 15–18, the EPA recommends less than 17 m^3/day for males and 12 m^3/day for females.[36] Although these inhalation rates may be useful markers, it is not straightforward to assess the quality of inspired air.

Air lead particles deposit on soils.

Soils are a legacy reservoir for exposure to lead dust outdoors and indoors.

Dust inputs, dust loading and storage in soils take place in the context of the city. At the scale of an individual home and surrounding property, contamination is dependent on of the city traffic congestion and location of industrial or manufacturing facilities. At some locations, especially inner-city communities, dust exposures are elevated, whereas in outer communities' dust exposures are attenuated. Under conditions such as drought, wind can easily pick up soil and re-suspend the contaminants into the air. This is especially common in seasonally dry and arid areas and puts children at risk of inhalation of hazardous transitory dusts.[37]

Ingestion

Hand-to-mouth and object-to-mouth behaviors are controlled by specific DNA-directed characteristics that begin in utero and continue into childhood.[36] This normal behavior exposes children to a variety of contaminants as they touch and mouth different objects.[38,39] In addition to exposures in outdoor play areas, toxicants from outdoor sources can be tracked into the home.[40] Toxicants are prevalent in nearly every child's play area.

Children's exploratory mouthing behaviors of non-food substances peak between one to three years of age and then decrease over time.[38,39] Exposure is

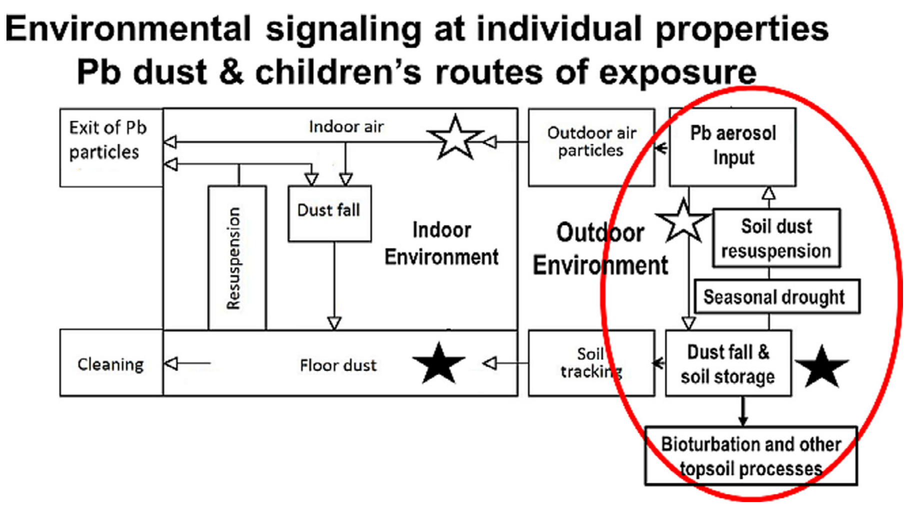

Fig. 5. Exposure pathways for particulate air lead inputs and the deposition in outdoor soils and indoors at individual properties. Topsoil (~2–3 cm) lead undergoes a gradual decrease by about half in 10–20 years.[52]

exacerbated in children with pica, who often deliberately ingest soil and contaminants.[41] Geophagy is a unique form of pica that involves consuming soil as a cultural practice, and ingestions can be in excess of 50,000 mg/day. This practice is common in regions of Africa. While the prevalence of geophagy is not well documented, studies estimate that the behavior is practiced by 28−84% of some studied populations.[41,42]

Fig. 5 illustrates the exposure pathways for lead in air and soil. Open stars represent inhalation and closed stars represent ingestion pathways. As illustrated on the right side of Fig. 5, the critical key to environmental signaling is the aerosol input whereby inhalation and ingestion are substantial when aerosol inputs are large and diminished when aerosol inputs are small. Soils then become a reservoir and source of lead dust.[43,52] Aerosols and soil dust freely move into home interiors and track in on footwear.[40,44,45] In this way the legacy of aerosol lead dust inputs into soil develops into a route of multiple inhalation and ingestion exposure pathways in outdoor and indoor environments.

Other pathways of exposure

Water can transfer environmental contaminants throughout the hydrologic cycle. In this way, toxicants are deposited in local water sources and groundwater, which can lead to human ingestion.

Dermal absorption is another method of exposure and is tied closely to investigative behaviors in children. Children often explore their environments with bare feet and hands, increasing the surface area of exposure. Although the best practices of measuring the magnitude of dermal exposure are often debated, many studies have shown that dermal absorption is a significant pathway for chemical exposure.[49] Children also have a greater body surface area compared to adults. Vegetable and fruit produce also can acquire toxicants during growth, and this contamination can indirectly affect those who consume the produce. These pathways of contamination include ambient pollutant deposition, absorption from soil, dissolution into water that supplies plants, and pesticide and fertilizer use. The toxicants can be carried up the food chain into meat, poultry, and dairy products.[50] Although toxicants can affect all who consume them, children are at unique risk due to the differences in variety of food consumed. Studies have shown that children most commonly consume dairy and fruit products[50] that may contain environmental toxicants.

Measuring exposure

Measuring exposure to soil ingestion is not straightforward, and the U.S. EPA has identified three methodologies to do so. These include the tracer element method, the biokinetic model comparison method, and the activity pattern method. Each method has limitations in estimating true ingestion rates.[46]

- The tracer element method quantifies the amount of soil ingested based on the presence and quantity of tracer elements measured in feces and urine.
- The biokinetic model comparison method compares direct measurements of biomarkers with predictions from a model including all possible modes of exposure to create an aggregate exposure evaluation.
- The activity pattern method combines information about behaviors with time spent in various locations to evaluate potential exposure

The U.S. EPA has chosen to use all three methods, with an emphasis on the biokinetic model comparison method, to make recommendations on maximum soil ingestion values in the Child-Specific Exposure Factors Handbook.[47] The handbook recommends a maximum average soil and dust ingestion of 60 mg/day for children ages 6 weeks to 1 year and 100 mg/day for children ages 1 year − 21 years. Ingestion is defined as pica when rates reach 1000 mg/day.[48]

As children explore their home and outdoor play environments, they are exposed to many toxicants that can have serious health effects.[51] Although it would be impossible to completely protect children from exposure to every hazardous substance in their environment, there are many actions that can, and should, be done to minimize the exposure risks. When evaluating these risks, it is important to realize the interactions between pollutants in the soil, air, and water and how these exist in a dynamic environment which constantly alternates between storing and transferring toxicants from one place to another.[52]

Toxicants in soil, air, and water exist in a dynamic environment.

Conclusion

Children can be exposed to hazardous substances through many exposure routes. Although many steps have been taken to decrease the contamination of water and air toxicants, addressing soil as an important source of toxicants is usually ignored. Soil contamination must be proactively addressed in a manner similar to air and water pollution.

Declaration of competing interest

None of the authors have any conflicts of interest to disclose.

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Soil toxicants that potentially affect children's health

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Soil pollution is a global phenomenon, and children are uniquely susceptible to the wide range of toxicants that persist in topsoil. Given their increased exposure through mouthing activities, increased body surface area, likelihood of breathing air closer to soil, and immature immune and elimination systems, it is essential to understand the mechanisms of children's exposure and the potential health effects of toxicants found in soil. Here we describe the sources and toxicological profiles of a range of inorganic and organic soil contaminants, including arsenic (As), cadmium (Cd), lead (Pb), mercury (Hg), benzene, toluene, ethylbenzene and xylenes, chlorinated dibenzo-*p*-dioxins, polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), per and polyfluoroalkyl substances (PFAS), as well as agricultural and domestic sources of pollution. The aim of this article is to increase awareness regarding the risks and health impacts of contaminated soil, and to encourage further research and efforts aimed at mitigating children's exposure.

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Introduction

Health effects of soil pollution vary widely depending on pollutant type, level of exposure, and vulnerability. Children are particularly vulnerable to a wide variety of soil contaminants because of their specific behaviors and their unique body physiology.[1] Common pollutants found in soil environments from both natural and anthropogenic sources are outlined below. Important health effects secondary to exposure to these pollutants are also described as well as their influence on environmental signaling cascades.

Numerous health effects are associated with toxicants found in soil.

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Epidemiology

Humans have been mining and concentrating subsurface materials at Earth's surface for thousands of years. People living on Michigan's Keweenaw Peninsula, for example, mined copper and subsequently left residues of lead, titanium, magnesium, and iron in lake sediments 8000 years before the present.[2] Early traces of soil or sediment pollution have been found throughout the globe,[3] and soil contamination has become increasingly extensive since the Industrial Revolution. Although the development of technology is often rapid, the establishment of policies and regulations to curb toxicants typically trails the rapid advances of industrial productivity. Most industrialized countries have established policies for recognizing and regulating soil pollution, but actions do not keep pace with development. Clinical measurements and techniques for quantifying the degree of soil contamination as well as its effects on human health remain largely under-characterized. Lack of access by environmental regulatory agencies, lack of research, and limited resources for remediation further complicate such tasks. Additionally, most studies focus on specific geographical areas and are therefore limited in scope.

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One large scale study conducted by the U.S. Environmental Protection Agency (EPA) in 2000 presented an initial effort to collect and analyze existing and readily available data on measures relevant to children's health and the environment. This report, called *America's Children and the Environment (ACE),* compiled data on children's health and the environment, detailed exposures and changing trends in children's health throughout the past two decades, informed discussions on improvements, and helped track trends in children's environmental health to minimize impacts. The most recent revision of this report was published in October 2019.[4] The report found that as of 2018, approximately 2% of children in the U.S. were living within one mile of a Corrective Action or Superfund site that may not have had human health protective measures in place. This proportion differed by race: about 3% of Black, Asian, American Indian/Alaska Native, and Hispanic children, 4% of children from "All Other Races," 7% of Native Hawaiian and Other Pacific Islander children, and 2% of White children were found to live in proximity to such sites. 70% of Superfund sites were located within 1 mile of federally assisted housing, which highlights the environmental injustice of this issue and the disproportionate burdens of exposure placed on low income communities and communities of color.[5–7]

Children are unique

Children are more susceptible to toxicants than adults, given their increased exposure through mouthing activities, increased body surface area, breathing air closer to soil, and immature immune and elimination systems. One example of an immature physiological system can be illustrated by arsenic metabolism. While an adult can methylate arsenic compounds into less toxic compounds for elimination, a child's ability to do this is not fully developed and children are thus less able to detoxify the compound.[8]

Inhalation

Dust particles that can reach the lung and settle in the alveoli without being filtered by the body's natural mechanisms can cause long-term health damage. For example, extremely tiny exhaust particles (<2.5 μm) from tetraethyl lead (TEL) additives in gasoline were inhaled, passed by the body's natural removal mechanisms and became absorbed directly into the blood stream. As a result, blood lead (Pb) levels were directly related to the quantity of Pb aerosols from gasoline. Blood Pb declined in step with the phaseout of leaded gasoline that began in 1975.[9] Inhaled metal 2.5-micron particles enter the blood stream and do not cause obvious symptoms because the inhaled particles are widely distributed throughout multiple organ systems. This concern was expressed by Yandell Henderson, Yale physiologist, during the 1925 hearings on public health concerns about allowing the use of TEL in gasoline.[10]

Direct damage to the lung also occurs from inhalation of dust particles that settle in the alveoli without being filtered by the body's natural mechanisms. A commonly inhaled dust particle is silica. Quartz silica deposits in the alveoli and causes irritation and fibrosis. This can ultimately cause restrictive pulmonary disease. Other commonly inhaled dust particles causing lung disease include toxicant asbestos, coal dust, beryllium, along with bacteria, animal proteins, and mold toxins.[11]

Although exposure to particles is not limited to the younger population, children are uniquely vulnerable to adverse effects given their immature physiology and increased exposure rates. Physiological differences include underdeveloped lungs that are less able to repair damage, mouth ventilation that limits filtration by the nasal passages, and higher baseline ventilation rates that inspire pollutants more deeply into the lung, increasing exposure and delaying clearance.[12] Together, these features can make children more susceptible to acute respiratory disease and asthma. In 2017, 8.4% of U.S. children were found to have asthma; the rate of emergency room visits for asthma and other respiratory causes was 760 visits per 10,000 U.S. children in 2016.[4]

Ingestion

The U.S. EPA soil lead standard for residential properties with Federal funding ranges from 400 μg/g (ppm), for bare soils where children play, to 1200 μg/g for remaining areas. Soil ingestion is less likely than dust inhalation to result in widespread systemic health effects, and more likely to result in gastrointestinal effects. Geophagy is an extreme example of soil ingestion, but it is not common in the U.S. Geophagy provides an example of the health effects that result from excessive ingestion. As discussed previously, children ingest soil at a much higher rate than adults, making them susceptible to the contents of the soil. Geophagy has been shown to have negative health consequences including reactions to lead or other anthropogenic toxicants, and parasitic organisms including helminths and *Clostridium tetani*, chronic intestinal blockage, and even excessive tooth wear.[11] Although some of these effects are likely limited to ingestion of large quantities of soil, they may occur with even small ingested soil quantities.

The neurologic system is especially vulnerable to exposure to metals and pesticides, and even small amounts of inhalation and ingestion can cause far reaching and potentially irreversible effects. Lifetime body burden begins early and, depending on the toxicant, continues throughout life. Studies are being conducted to quantify the body burden in adulthood. Rolf Tore Ottesen, geochemist and researcher living in Trondheim, Norway (and major part of the team responsible for Norway's Clean Soil Act) had his blood tested; many exotic metals and organic toxicants were found as illustrated in Fig. 1.

Most health impacts from toxicant exposure occur as a result of inhalation and ingestion.

Most health impacts from toxicant exposure occur as a result of inhalation and ingestion.

The following section outlines some common soil contaminants and their health effects on children. This list provides examples of soil toxicants that can affect children but is not comprehensive. Toxicants of major interest are listed in Table 1.

Inorganic contaminants: metals and metalloids

- Arsenic
  - Arsenic (As) is a common and prevalent element found in many environments. Arsenic exposure comes mainly from contaminated water, crops, and tobacco.[13] Arsenic also may be especially common underneath and near chromium-copper-arsenate (CCA) treated wood playground equipment at public parks.[14] Arsenic is used in photoelectric devices, glassware, Pb-acid batteries, and in copper alloys. Until the 1970s, arsenic was used extensively for manufacturing pesticides. Although the prevalence in pesticides has decreased, organic As compounds are still in production.[15]
  - Arsenic poisoning can occur acutely or through chronic exposure and subsequent accumulation in the body. In acute poisoning, symptoms are generally associated with the gastrointestinal tract and include nausea, vomiting, abdominal pain, and diarrhea. Other signs and symptoms may include a metallic taste or a garlic odor to breath and stool.[16] More severe consequences of acute arsenic poisoning include acute encephalopathy, acute kidney injury, severe hypotension, respiratory failure, and QTc prolongation leading to life-threatening cardiac arrhythmias.[17]
  - Chronic exposures are more likely to occur in children. Chronic arsenic exposure occurs through ingestion of small amounts of arsenic over time or through dermal contact. Chronic exposure through drinking water has been shown to cause various skin lesions, neurological effects, high blood pressure, diabetes mellitus, respiratory diseases, and a range of cancers associated with the skin, lung, and bladder.[18] The effects of chronic exposure on the neurologic system may result in progressive numbness and tingling of the soles and palms.[19]
- Cadmium
  - Cadmium (Cd) is one of the most ecotoxic metals, adversely affecting all biological processes in humans, animals, and plants. The main uses of cadmium are in battery production, yellow pigment, coatings and stabilizers. Because of its particular physical and chemical properties, cadmium is also added to alloys and various plastics.[15] Cadmium in soils and surface environments is from anthropogenic sources such as rock phosphate fertilizer, fossil-fuel combustion, cement manufacturing and metallurgy, municipal waste and sewage, as well as atmospheric deposition. In most Western countries, rock phosphate fertilizer and atmospheric deposition alone account for over 90% of the anthropogenic sources of cadmium.[20]
  - Cadmium toxicants, like other industrial forms of soil pollution, are highly variable in air, water, and soil. Anthropogenic sources of cadmium in

Fig. 1. Body burden of toxicants in Rolf Tore Ottesen's blood of Norway. Toxicants appear in blood, fatty tissues, and bones of people throughout the world. First published in Adresseavisen, Norway, 4 Nov 2011, with Dr. Ottesen's permission.

TABLE 1. Toxicants, years of life lost, and deaths per 100,000. Re-drawn From Lanphear et al. 2005.[28]

Toxicant	Years of life lost (per 100,000)	Deaths (per 100,000)
Asbestos	173.9	11.7
Lead	113.3	8.7
Arsenic	6.9	8.7
PAHs	1.3	0.05
Cadmium	0.2	0.0

the environment are attributed mainly to mining, refining, and burning of coal and fossil fuels. Cadmium in the environment does not break down, but instead changes form. Some forms dissolve in water, whereas others bind strongly to soil particles.[21]

- Cadmium first became a concern in the 1960s, when a painful bone disease 'itai–itai' was reported in Japan. The Cd contamination was a result of transported waste from a zinc–lead (Zn–Pb) mine deposited by a river into rice paddy. People who consumed the toxicant polluted water and rice were found to have accumulated high quantities of cadmium that caused a serious osteoporosis-like bone disease referred to by the Japanese as 'itai–itai byo' or 'ouch–ouch disease'.[21]
- Regardless of its chemical form, exposure to cadmium can cause severe health effects, including lung and kidney damage. The Agency for Toxic Substances and Disease Registry (ATSDR) has concluded that cadmium exposures are likely or suspected causes of cancer in humans.[22] Cadmium also has been shown to be an endocrine-disrupting chemical with estrogenic properties.[21] Although more research is needed on how cadmium affects younger populations, animal testing has revealed that younger animals absorb more cadmium than adults, which likely has negative influences on learning, behavior, and development.[22]

○ Lead (Bly)

- Lead (Pb) is a common and dangerous environmental toxicant. Its early use initially came from smelting during ancient times, particularly in Rome. Environmental contamination peaked with the use of leaded motor fuels and paint in the 20th century, although each of these uses has since been curtailed. Its negative health effects persist, and soils contaminated from airborne lead are an insidious exposure reservoir. Tetraethyl lead (TEL) is still used in aviation gas for reciprocating airplane engines in private aircraft, and nearly 60% of lead aerosols in the United States can be directly tracked to TEL additives in this fuel.[23] At the current time, the largest sources of lead production include lead-acid batteries for motor vehicles, as well as outdoor paints, pigments, ammunition, ceramic glazes, jewelry, toys, cosmetics, and medicines. Drinking water delivered through lead pipes and lead solder also can be contaminated.[24] The 2019 ACE report found that in 2005–2006, 13% of children ages 0–5 years lived in homes with interior lead dust hazards and 11% lived with interior deteriorated lead-based paint hazards.[4] The median concentration of blood lead in children between 1−5 years was 0.7 ug/dL in 2013−2016, however the median was 0.9 ug/dL in Black children and 0.7 ug/dL in White, Mexican-American children, and children of "All Other Races/Ethnicities."[4]

  - Lead exposure of children primarily influences brain and nervous system development. Acute high exposure can result in convulsions, coma, and death. Residual effects can include mental disability and behavioral disorders, including violence.[25−27] At lower exposure levels, lead exposure can cause injury to brain development manifesting as reduced intelligence, reduced attention span, increased antisocial behaviors, and poor school performance.[28] It can also cause a variety of health effects, including anemia, hypertension, renal injury, reproductive organ injury, and damage to the immune system.[24] There is no known safe level of lead exposure.[29]

- Mercury
  - Mercury (Hg) is a global toxicant. The US Clean Air Act Amendments of 1990 identified Hg as a hazardous air pollutant due to its toxicity, availability, potential bio-accumulation in food chains, and human health risks.[15] Common uses of Hg include dental amalgam fillings, analytical instruments, batteries, florescent lamps, wood fillers, and as a fungicide in paints and pesticides. Many of these products have become regulated, but Hg continues to be used in batteries, and compact fluorescent lights. Common sources of environmental Hg arise from its use as an amalgamator of small gold particles from soil and sediments when mining soil and sediments.[15]
  - Mercury has been found in higher concentrations in urban soils than ambient background concentrations in soils outside of cities.[30] Urban environments may receive Hg inputs from a variety of human activities such as coal-fired power plants, waste incinerators, steel mills and foundries, cement kilns, utility and industrial boilers, brick refractories, refineries, landfills, and asphalt plants. Food web accumulation occurs where environmental conditions promote bacterial conversion of urban Hg loads into methylmercury. As a result, unsafe levels of Hg in fish can occur in urban streams flowing from areas with high Hg concentrations in the soil, streambed sediment, and water, presenting above-average risks for Hg exposure to those who consume fish from urban stream and coastal waters.
  - Mercury is found in three main chemical forms: elemental (metallic, Hg^0), inorganic compounds (I-Hg), and organic compounds (such as methylmercury, MeHg).[31] Most Hg exposure occurs from methylmercury from sources such as seafood, inorganic mercury from food, and elemental mercury vapor from dental work.[32] I-Hg is accumulated mainly in the kidneys where it causes kidney damage, while Hg^0 is generally inhaled, and rapidly absorbed and distributed to all major organs.[31] Hg may have potentially permanent impacts on brain and nervous system development of fetuses and children, on human endocrine systems.[33,34] High Hg levels in children causes learning disabilities, psychological disorders, and other neurological disorders.[35]

Organic contaminants: persistent, volatile, and pesticides compounds

- Benzene, toluene, ethylbenzene and xylenes
  - Benzene naturally occurs from volcanoes and forest fires. As a toxicant, large quantities of benzene are used to manufacture plastics, synthetic fibers, and rubber. Benzene, toluene, ethylbenzene and xylenes (BTEX) have been extensively used as raw materials, organic solvents in industrial processes, and in pesticides. Because these materials are highly volatile and soluble, BTEX can easily be dispersed in the environment at regional scales. Sources of BTEX emissions include combustion of wood and fuel, traffic, adhesives, degreasing agents and aerosols.[36]
  - BTEX in soil can either evaporate to the air or migrate deeper in the soil profile. Small dust particles can also be suspended and distributed across large areas, eventually redepositing back to the soil surface. Exposure to such dusts in the air, soil, water and plants can cause adverse effects to those exposed through inhalation or ingestion.[37] Microbes can facilitate biodegradation of BTEX over time.[38]
  - BTEX are known neurotoxicants, with potential for bioaccumulation through the food chain. Chronic exposure to toluene, ethylbenzene and

xylenes has been associated with adverse effects on human nervous systems, respiratory systems, liver and kidney function.[39] When BTEX is detected in air, soil, dusts and groundwater, they may potentially have adverse effects through inhalation, dermal adsorption, and ingestion. Benzene, in particular, is classified as a carcinogenic compound.[40]

- Chlorinated dibenzo-*p*-dioxins
  - Dioxins are among the most hazardous anthropogenic toxicants in the environment, and their toxicity has been extensively studied in both humans and animals. They arise as unintentional byproducts of industrial operations. Sources of exposure include chlorinated pesticides, treated lumber, municipal waste, and incineration.[41] Polychlorinated dibenzo-p-dioxins (PCDDs), dibenzofurans (PCDFs) and other persistent organic pollutants (POPs) can persist in soils, sediments and waste repositories for extended periods of time, ranging from decades to centuries. Application or improper disposal of pesticides, polychlorinated biphenyls (PCBs) and other organochlorine chemicals, as well as waste recycling, has created contaminated sites. The leachates and groundwater impacted by these sites require ongoing monitoring and further remediation. In 1994, the U.S. EPA concluded that contaminated sites and other reservoirs of these substances were likely to become the major source of contemporary pollution problems.[42]
  - Many of these hydrophobic and lipophilic compounds are highly resistant to metabolism in vertebrates, including humans. Dioxin-contaminated soil can result in biomagnification in food chains, and high tissue concentrations may be found in top predator species.[43] Oral pathways are the most common route of exposure. Ingestion of contaminated soil, water, fish, beef, dairy, and vegetables may be significant in certain areas. Associated health impacts include chloracne, dermal hyperpigmentation and hirsutism, elevated hepatic enzyme levels, increased risk for diabetes, and altered reproductive hormone levels.[41]
- Polychlorinated biphenyls
  - Polychlorinated biphenyls (PCBs) are a group of over 209 industrial toxicants that have been found in almost every component of global ecosystems, including air, water, soil, sediments, fish, wildlife, and even human tissues and milk.[44] Although they have not been manufactured in the U.S. since 1977, they still exist in pre-1979 fluorescent light ballasts, electrical capacitors and transformer oils. They are not easily broken down and can bind strongly to soil particles.[45] PCBs used in construction materials such as caulking used around windows, expansion joints, and bath fixtures are sources of contamination in building interiors and surrounding exterior soils. PCBs in soil can be mobilized, which can present further hazards for leachate and groundwater.[46]
  - PCBs can be absorbed in the gastro-intestinal tracts of animals, especially when ingested with organic solvents or dietary lipophilic carriers, and when bound to soil particles.[47] Responses to PCB exposure include developmental and reproductive toxicity, dermal toxicity, endocrine effects, hepatotoxicity, carcinogenesis, and the induction of diverse phase I and phase II drug-metabolizing enzymes. When short-term occupational exposure occurs, the effects may be reversible, with no changes in overall mortality or cancer mortality being reported. Research has demonstrated developmental deficits in infants and children associated with in utero exposure to PCBs.[44]
- Polycyclic aromatic hydrocarbons
  - Polycyclic aromatic hydrocarbons (PAHs) are organic sources of hydrocarbons that are found in soil and persist in the environment due to anthropogenic combustion activities.[48] PAHs include over 100 different compounds formed during combustion and can occur naturally (from burning wood or meat) or as a product of manufacturing (in coal tar, plastics and pesticides). A study in Mexico found that sources affecting children included biomass combustion, brick kilns, sanitary landfills with waste combustion, and automobile traffic.[49] Each of these sources can deposit PAHs into the soil, where they can be ingested by children, absorbed into crops, or leached into water sources. PAHs have been studied in soils in New Orleans, LA and Detroit, MI, where they were closely associated with lead and zinc concentrations, and directly related to vehicle traffic flows.[50,51] Although PAHs can break down with sunlight, or from microorganism activity, they can also cling to soil particles and contaminate groundwater, plants and animals.[52]
  - Exposure to PAHs has been linked to ADHD-like behaviors and cancer. Most research

evaluates exposure to PAHs as a result of air pollution.[53] Children with prenatal exposure to PAHs have higher rates of cognitive disability later in life, suggesting that PAHs are harmful to the developing fetal brain.[54] PAHs have been shown to cause skin irritation and inflammation in an acute setting, and decreased immune function, cataracts, kidney and liver damage, breathing problems, and hemolysis, depending on the route of exposure.[55] More research to examine the effects of soil PAHs on health is needed.

- Per and polyfluoroalkyl substances
  - Per and polyfluoroalkyl substances (PFAS) are a group of human-made compounds that include perfluorooctanoic acid (PFOA), perfluorooctane sulfonate (PFOS), GenX and a number of other chemicals. PFAS have been used for a range of industries worldwide, and have been in production in the U.S. since the 1940s. PFOA and PFOS are the most studied forms, and have shown to be persistent in human bodies and the environment.[56] These compounds can be found in food, particularly when packaged in materials containing PFAS, processed with PFAS in equipment, or grown in soil or water contaminated by PFAS. Commercial household products containing PFAS include stain resistant and water repellent fabric, nonstick cookware (such as Teflon), polishes, paints, cleaning products, and fire-retardant foam. Workplace exposures include production and manufacturing that use PFAS (such as electronics industries and oil extraction). Drinking water also may be a source of exposure, particularly if localized pollution from manufacturing, landfill, wastewater treatment, or firefighting training sites. Consuming fish and animals with accumulated PFAS also can be sources of exposure.[57]
  - PFAS can lead to adverse health outcomes in humans, as well as laboratory animals. Most health data are focused on PFOS and PFOA as a result of their long history of scientific study, but adverse health effects of other related chemicals are emerging. In 2000, analyses of serum samples from the National Health and Nutrition Examination Survey (NHANES) found that PFOS and PFOA were detectable in all Americans.[56] PFAS are transferred through the placenta and mother's milk, and concentrations in children tend to be higher than in adults. PFOAs are "likely to be carcinogenic in humans," and immunological impairments may also result from exposure.[58] Common findings indicate associations with increased cholesterol levels, as well as reproductive and development impairment, liver and kidney damage.[59]
- Agricultural and Domestic Sources of Pollution
  - Pesticides and herbicides are commonly used in both large-scale industrial agriculture and small gardens. These chemicals can persist in the environment, causing both acute and chronic toxicity. The most commonly used pesticides include organochlorines, pyrethroids, carbamates, organophosphates, and nicotinoids.[4] Organochlorines such as DDT were removed from the market due to their extreme adverse ecological effects to bird populations, and tendencies to persist in the environment. Pyrethroids and carbamates also target the nervous systems and result in many detrimental health effects.
  - Organophosphates target the nervous system by inhibition of acetylcholinesterase, leading to overstimulation of muscarinic and nicotinic receptors. Acute toxicity of organophosphates includes diaphoresis, salivation, lacrimation, urination, diarrhea, emesis, miosis, bradycardia, and bronchospasm. Exposure can also cause muscle fasciculations, cramping, weakness, anxiety, confusion, ataxia, tremors, seizures, and coma. In children, the most common presentation is seizure and coma.[60]
  - Chronic exposure to pesticides can affect neurological and behavioral development in young children, leading to altered reflexes, ADHD, and deficient psychomotor and neurological development.[61] Higher levels of DDT in children are associated with poorer performance on verbal and memory scale scores.[62]
  - Glyphosate (*N*-(phosphonomethyl) glycine) is an herbicide first used to control weeds in 1974. Glyphosate use has increased rapidly in recent decades, and in 2012, approximately 127,000 tons were applied to fields in the U.S. and 700,000 tons were applied worldwide.[63] This increase occurred particularly after a number of glyphosate-resistant crops such as soybeans, canola, cotton, and corn were genetically engineered. The upward trend in glyphosate use will likely contribute to increases in environmental loadings and human exposures to this herbicide and its metabolite aminomethylphosphonic acid (AMPA).[64]

- Correlations between glyphosate use and a variety of human diseases including forms of cancer, kidney damage, ADHD, autism, Alzheimer's and Parkinson's disease have been described.[65] Glyphosate was listed as a probable carcinogen by a working group of 17 experts from 11 countries convened in 2015 by the International Agency for Research on Cancer (IARC).[66]
- The evidence linking glyphosate exposure to non-Hodgkin's lymphoma in humans is from mostly agricultural exposures, mainly in the U.S. and Sweden published since 2001. The industrial farming application of glyphosate is massive and includes vast areas of the rich farmland of the U.S. (See Fig. 2). On the basis of the IARC determination many countries and communities currently restrict glyphosate.[66]

Increased efforts to limit toxicant exposure must be widely adopted.

Conclusion

Exposures to toxicants in soil can affect children's health. Many of the more common pollutants and their effects are outlined to characterize the range of soil contaminants and their impacts. There has been some progress towards decreasing the burden of soil contaminants through efforts such as banning the use of lead in automobile gasoline; however, increased efforts to limit exposure to a wide range of soil toxicants are needed. Exposures to toxicants in air, water, and soil are a serious problem. This worldwide issue deserves more attention in order to limit the health risks to children. Fortunately, there are many steps that can be taken to decrease the pervasiveness of soil pollution and limit the impacts on children's health.

Increased efforts to limit toxicant exposure must be widely adopted.

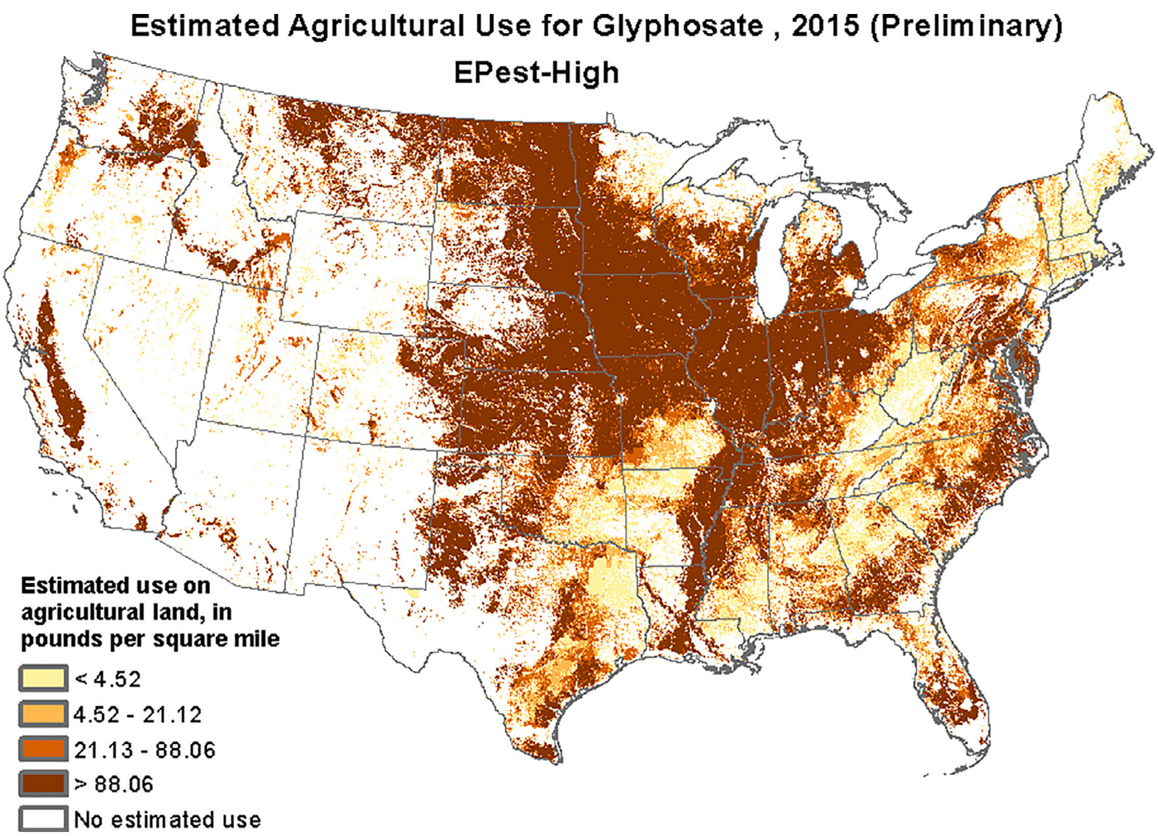

Fig. 2. Estimated use of glyphosates (Roundup) on agricultural land in pounds (0.45 kg) per square mile (2.6 square km).

Conflict of interest

None of the authors have any conflicts of interest to disclose.

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Quantifying soil contamination and identifying interventions to limit health risks

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Numerous toxicants contaminate soil and negatively affect the environments that children explore. Accurately measuring these toxicants and characterizing the level of soil contamination may be difficult and must include measurements of both the environmental concentrations and the exposure responses of human populations. This article reviews the current methods and technologies available for quantifying soil contamination. Several intervention strategies exist for limiting human exposure to contaminated soils and the strengths and weaknesses of these methods are discussed. Lastly, current policies on soil contamination and the importance of protecting vulnerable populations by developing means to improve health conditions for children are reviewed.

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Introduction

Numerous toxicants that contaminate the environments that children explore may negatively impact children's immediate and/or long-term health. Fortunately, much can be done to substantially decrease these exposures and resulting health risks. This paper describes the important technologies that are used to further characterize the quantity of toxicant, exposure risks, and important interventions for limiting those risks. While remediation techniques are straightforward, and the ethical impetus seems clear, the policies surrounding environmental health and soil health are more ambiguous. More advocacy must be done for a healthier environment for children.

Quantification methods

With so many types of toxicants in the environment, it is important to develop methods to measure both the environmental concentrations and the exposure responses of human populations. The impetus to measure contaminant quantities in the soil lags behind the incentive to measure human exposure. Likewise, the motivation to measure the human health outcomes of exposure lags the economic stimulus for industrial production resulting in pollution. Therefore, in order to prevent detrimental health effects, a proactive, rather than a reactive, approach must be adopted for the protection of humans and the environment.

Toxicants in soil easily can go undetected because they are frequently invisible. Although the presence of paint chips, soil discolorations, strong odors, and a failure of vegetation growth may indicate problems in the soil, such issues may also be indicative of soil quality issues (i.e., lack of drainage, compaction, limited organic matter, etc.) and not necessarily be indicative of contamination. Many plants have effective mechanisms to limit toxicant uptake and will grow to maturity even when contaminants are present in soil.[1]

Sending soil samples to laboratories is the most reliable and effective way to assess contaminant concentrations. Screening for metals with an x-ray fluorescence (XRF) analyzer can provide rapid and accurate results. Quantitative metals results also can be obtained by more sophisticated methods involving soil digestion or extraction and mass-spectrometer analyses. Although test kits are available for metals, mercury, organochlorine pesticides, pentachlorophenol, and polycyclic aromatic hydrocarbons (PAHs), many test kits available to consumers can be unreliable. Additionally, certain testing methods for organic pollutants may not be generally

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available or affordable for individual households. Most agricultural extension offices provide support to individuals for assessing the presence of a wide variety of soil contaminants, but this resource may not be well known to the general population.

One easy and inexpensive method for measuring lead on interior floors involves wiping a measured surface area of the floor. The current standard of lead dust for interior floors is 107.5 $\mu g/m^2$ (10 $\mu g/ft^2$).[2] The Potentials Lead on Play Surfaces (PLOPS) method, developed at Xavier and Tulane University in New Orleans, Louisiana, measures surface lead loading and the exposure potential of soil lead.[3] Metal loading in soil is measured by placing a wipe attached to a plastic bag on the soil surface—similar to placing a hand on the soil surface. Although quantities of metals in soils typically are measured by content, surface loading is a more relevant measure for a child at play because it measures the quantity of metal directly obtainable from the soil surface.[4,5] The critical observation is that the lead loading of outdoor surface of the soil that meets the current U.S. Environmental Protection Agency (EPA) residential soil standard (400 ppm) is about 150 times higher than the current EPA standard for lead dust on indoor floors. The association between soil lead content and surface loading is consistent with the observed lead exposure response between children's blood and soil lead content disparities for a city.[6]

Fig. 1 provides an example of the association between lead content and lead loading of the soil in New Orleans. The lead loading was calculated from Mielke et al.[7]; $SL = -7.4 + 0.41 \times PLOPS^{0.97}$ (SL = soil lead and PLOPS = soil lead loading). This study showed that the quantity of lead measured in soil containing 400 $\mu g/g$ has a soil loading of 16,200 $\mu g/m^2$ (1500 $\mu g/ft^2$) or around 150 times more lead than is permissible in the interior floor. The New Orleans soil lead survey visualizes the environmental signaling disparities and potential children's health issues derived from soil in New Orleans. Children's blood lead directly corresponds to the soil lead and lead dust exposure in communities of New Orleans.[7]

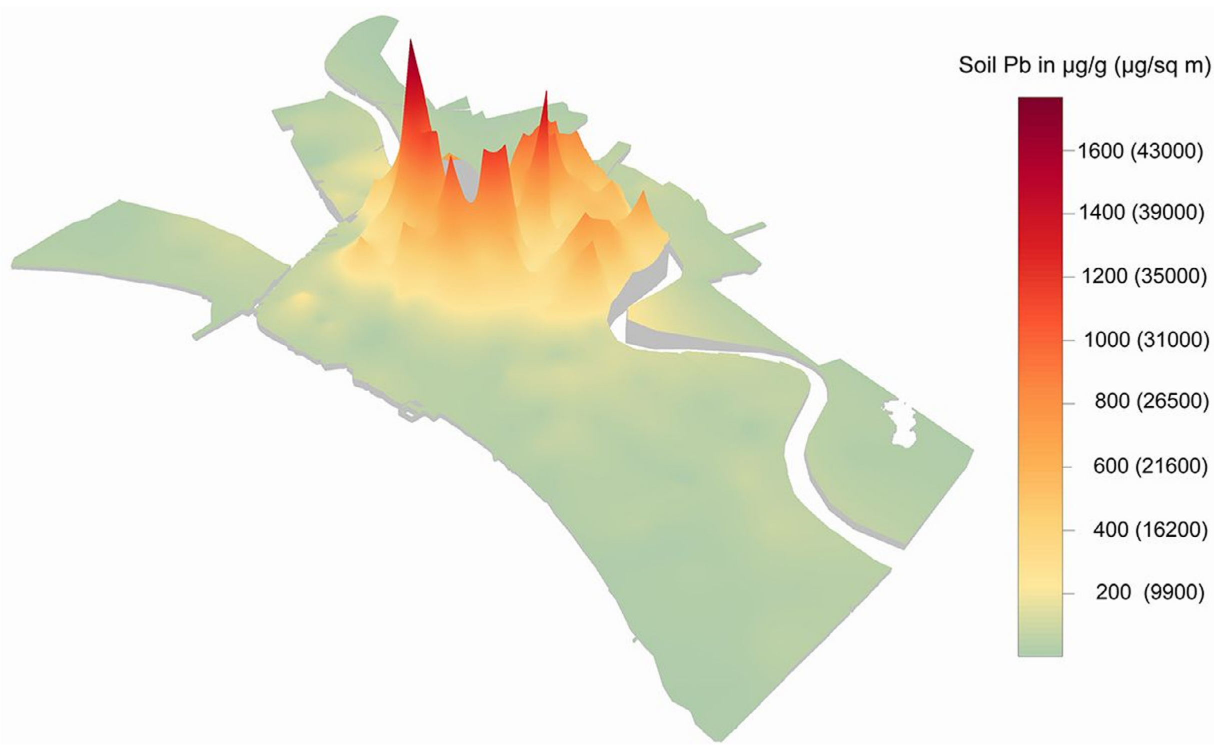

Fig. 1. The lead loading of the soil surface vs. the lead content of topsoil. Note the disparity in the amount of lead in the interior communities of New Orleans compared with the outlying communities of the city. Children's blood lead is closely associated with the pattern of soil lead and lead dust loading of the soil surface. Credit: Creative Commons, Mielke HW, Gonzales C, Powell E and Mielke PW. Evolving from Reactive to Proactive Medicine: Community Lead (Pb) and Clinical Disparities in Pre- and Post-Katrina New Orleans Fig. 2, page 7487. *Int. J. Environ. Res. Public Health* 2014, *11*, 7482–7491; https://doi.org/10.3390/ijerph110707482.

Fig. 2. Example of soil intervention using geotextile and clean soil emplacement. In hours the soil lead on the surface of the children's play area decreased from ~700 ppm to ~5 ppm. The cost was about $100 per child for this activity. Photo credit: HW Mielke, Department of Pharmacology, Tulane University School of Medicine.

Margin of safety

A soil lead standard that adequately protects children from exposure to soil lead can be developed from these data.[8,9] The current EPA standard for lead in residential soil of 400 ppm does not include a margin of safety. The margin of safety applied to pharmaceutical products is at least a factor of 10. If the same margin of safety were applied to soil lead, then a safer standard with a margin of safety for soil lead would be 40 ppm, not 400 ppm. In fact, in New Orleans, children living in outlying communities where the community median soil lead is less than 40 ppm exhibit blood lead levels that are less than 2 μg/dL.[9] Fig. 1 demonstrates the fundamental issue. If the amount of lead in soil is reduced, then attenuation of soil lead effectively reduces children's blood lead levels.[8]

Interventions

Many federal and state agencies accept that soil lead contamination is a health problem. Acceptance is not universal, however. For example, on September 27, 2018 the Commissioner of the New York City Department of Health and Mental Hygiene stated at a City Council hearing that soil is "not a significant source of lead exposure for children in New York City.[10] Statements such as this complicate the process of obtaining measurements of soil lead contamination or engaging in activities to address the urban soil problem by preventing understanding about an invisible toxicant in the environment.[4]

The U.S. EPA has outlined three main methods for lowering human exposure to contaminated soils: removing the soil and treating or disposing of it, treating the soil in place, or containing the soil in place to limit exposure risk. These techniques, specific to lead remediation, are described here, however, such techniques can be applied to most contaminant types.

- Dig and Haul
  - The most common mechanism for decreasing exposure risk is referred to as dig and haul. This process is exactly as it sounds; contaminated soil is excavated and transported to another area. Although this is a rapid way to reduce the

presence of in situ soil contaminants, the cost is high ($388 per square meter, or $36 per square foot). Shipping polluted soil to other locations does not reduce overall contamination; it only transfers it to another area. The process of distributing contaminated materials increases the potential for resuspension and deposition of contaminated particles. For these reasons, attention is being paid to "Green Remediation" in order to improve on aspects of dig and haul projects that are problematic.[4] The U.S. EPA defines Green Remediation as the practice of considering all environmental effects of remedy implementation and incorporating options to minimize environmental footprints in cleanup actions.

- Geotextile and clean soil emplacement
  - A relatively uncomplicated and low-cost approach was used in New Orleans, Louisiana to conduct soil lead intervention projects. Fig. 2 shows that the intervention only requires two components: geotextile and low contaminant soil.[5] Geotextile can be spread on the surface of contaminated soil in sensitive areas such as childcare play areas, parks, and elementary schools for a cost as low as pennies per square area. Bright orange geotextile is water permeable and provides a visible, protective layer between the contaminated soil beneath and clean soil above. Low contaminant alluvial soil to a depth of at least 15 cm (6 inches) can be spread on the surface of the geotextile.[5] This method costs $22 per square meter ($2−4 per square foot). It is a cost-effective way of decreasing *in situ* exposure risks that limits the additional risks associated with dig and haul techniques. If the cover is maintained, then burying the contaminated soil below the geotextile limits both current and future risk. Mapping soil toxicants presents an opportunity to educate future land users about legacy contamination and the responsibility to account for and proactively prevent exposure from the site. Obtaining uncontaminated soil, without disturbing other ecosystems may be a limiting factor in this process. As such, research is being conducted on manufacturing soil, or creating constructed Technosols, to meet this growing need.[6,11]

The photo (Fig. 2) of geotextile and low lead soil emplacement underway at a childcare center playground in New Orleans. Within hours the lead content of the soil surface was transformed from 700 ppm to 5 ppm.

- Phytoremediation
  - Phytoremediation refers to a suite of approaches involving the coordinated use of plants and their associated microbes to reduce the toxic effects of contaminants in the environment.[4] The process of phytoremediation has been shown to be a cost-effective method for decreasing concentrations of organic soil contaminants, with an estimated cost of about $10−35 per ton of soil to be decontaminated.[12] Unfortunately, because of extremely limited plant uptake, there is no known plant that is capable of soil lead phytoextraction or hyperaccumulation.[13] As a result, one of the major limiting factors of phytoremediation is that this method can only reduce concentrations of certain pollutants. Phytostabilization, however, the process through which plants stabilize or sequester contaminants in soil or water, is an effective way to reduce exposure to contaminated soil and maintain soil cover.
- Urban gardening
  - Urban gardening has proliferated over the past few decades and provides a wide range of social and ecological supports such as increased food access and fresh produce intake,[14−16] food justice and food sovereignty,[17−19] a range of health benefits,[20−22] as well as increasing community wellbeing.[23−31] Ecological benefits include reduced stormwater runoff,[32] increased biodiversity and habitat,[33,34] and carbon dioxide sequestration.[35,36] Gardeners growing in contaminated urban soils frequently add amendments such as compost, fertilizers, mulch, and a variety of organic residuals which can change both the overall concentration and bioavailability of contaminants in soil.[37] These materials can dilute the concentration of contaminants and may change the form that elements such as Pb take, by adsorption, complexation, or reduction.[38,39] Amending with phosphorus, in particular, has been shown to bind with Pb to form highly insoluble minerals.[40] Phosphorus additions may increase the availability of arsenic, however, and must be added in accordance with detailed procedures, which may be difficult for home gardeners to employ.[41] Phosphorus additions also

can increase nutrient loading to aquatic systems, leading to environmental issues such as eutrophication.[42] There are many different methods to test for Pb bioavailability, (or bioaccessiblity when conducted in laboratories) and it is difficult to compare results performed by different labs.[43]

- Growing plants in contaminated soils is essentially a phytostabilization method, and this practice also can increase organic matter in the soil from root exudates and decaying plant matter. These additions can dilute the overall contaminant concentration, change potential bioavailability, and can increase other biological activity and bioturbation, potentially moving contaminants down the soil profile.[44–46] Most edible crops employ a variety of mechanisms to limit Pb uptake, and proper washing renders most crops safe for consumption.[47] Dust or surficial deposition of contaminated soil can be a source of exposure so care should be taken to avoid growing food in contaminated soils.[48,49] Crop selection is also important, and fruits tend to be less contaminated than leafy greens or root crops.[50,51]
- Other common urban horticultural and agricultural practices include bringing in new soils, which is aligned with the clean soil emplacement intervention described above.

○ Other techniques

- Numerous other ideas for decreasing soil contamination include soil venting, soil washing, solvent extraction, and incineration. Unfortunately, these techniques have demonstrated limited success and are extremely resource intensive.

Although the above techniques focus on decreasing contaminant levels before exposure, many children already have been exposed, and there must be research done on tools to decrease levels in these children. The Cochrane Collaboration uses meta-analyses to evaluate the effectiveness of medical interventions. The Cochrane Collaboration found that typical interventions for elevated blood lead consist of education and household dust removal. While these interventions may decrease the amount of contaminated soil in homes[52] they have not been shown to be effective at reducing children's blood lead levels.[53] This is a dilemma for medicine, because while the clinical effects of pollutant exposure are known, an effective intervention for reducing blood levels is lacking. To date, no agreement has been reached about how to lower blood lead levels once elevated, and more research on this topic is needed.

Children's blood is measured to test for lead exposure. If the results are elevated (currently above 5 μg/dL) then attempts are made to find the source of exposure. This is secondary prevention and fails to meet the goal of primary prevention of finding the source of exposure in the first place. This is a critical ethics and policy concern for healthcare and medicine.

Ethics and policy

The abilities to detect and remediate contaminated soil have improved with time; however, our societal drive to act lags behind. In 1925, Yale professor Yandell Henderson warned about the ubiquitous use of lead, foreseeing that it would slowly grow to become an enormous problem.[54] He also suggested that "this is probably the greatest single question in the field of public health that has ever faced the American public...It is the question whether scientific experts are to be consulted, and the action of the Government guided by their advice; or whether, on the contrary, commercial interests are to be allowed to subordinate every other consideration to that of profit."[54] Dr. Henderson raised an important concept about the ethics behind protecting the health of the U. S. population over the interests of corporations, as far back as 1925. Although the public was warned about the adverse effects of this insidious toxicant, no action was taken to stop or prevent it. As has been clearly shown through research, children face increased risks of encountering contaminated soils and developing negative health effects from them, and therefore, end up bearing much of the ensuing burden. As such, it is crucial that action is taken not only to prevent future catastrophes from occurring, but also to identify the current risks to children's health and reduce these as much as possible. Figure 3, Children must not be used as the testing method for identifying lead in the environment. Children are not able to protect themselves and it is vital that adults, and especially health professionals advocate for children and adolescents.

In 1964 the World Medical Association published the Declaration of Helsinki policy statement.[55] This policy focuses on medical research with human subjects and has been accepted by scientific communities worldwide. Since its original publication, this statement has been amended seven times to increase its scope and clarify specific points. One such point of emphasis is the importance of protecting the health of

Fig. 3. Children's blood being drawn to test for lead. Photo Credits: Center image, HW Mielke, Tulane University School of Medicine; Right and left images, creative commons.

vulnerable populations, and particularly young children.[55] The policy defines vulnerable populations as individuals who are "at increased likelihood of incurring additional and greater harm" in the face of certain dangers. Children are clearly vulnerable, and it is the responsibility of society to keep them safe from the soil toxicants that they cannot themselves avoid.

The ethical obligation to remediate and improve the health of soil is clear. As such, there are numerous policies currently enacted to influence the interventions designed to decrease the health risks of certain contaminants in soil.

Soil lead pollution provides an important case study regarding the diverse regulatory guidance values for preventing exposure to contaminated soils.[56] Many researchers throughout the world have evaluated soil safety for children and continue to recognize harm at ever lower amounts of exposure, but the policies have failed to keep up with these discoveries. Fig. 4 shows the variation in guidance values for soil lead that have been promulgated by nations around the world.[56] The current U.S. guidelines for soil intervention were established prior to the Center for Disease Control and Prevention's most recent understanding regarding lead that "no known level of exposure is safe for children."[57] Currently, given that there is no known safe level of lead exposure for children, and because it lacks a margin of safety and fails to accept the strong

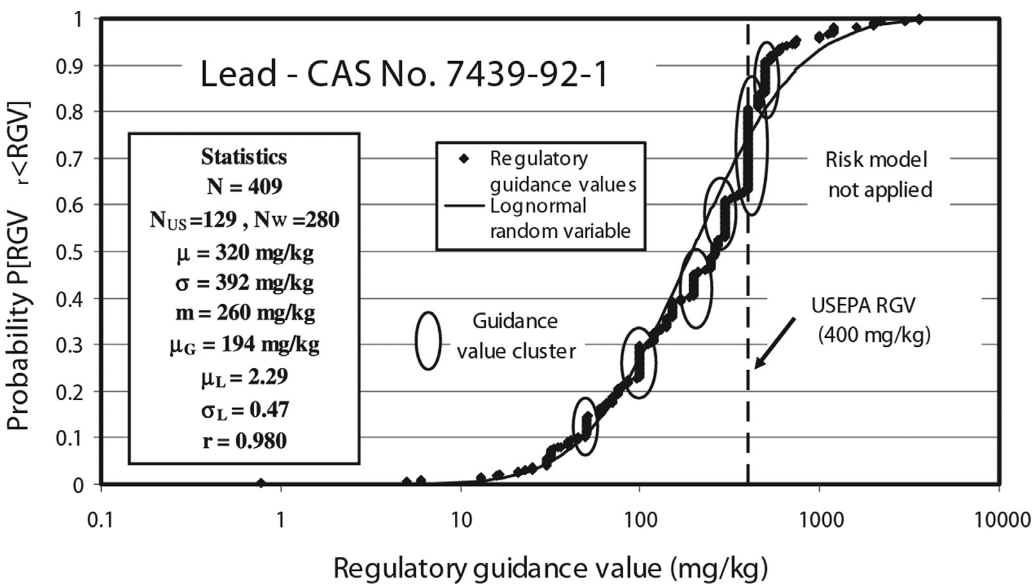

Fig. 4. Range of guidance values for soil lead promulgated by nations. The Russian soil lead standard is 32 mg/kg (ppm), Norway's standard is 60 mg/kg, and the US standard is 400 mg/kg. As shown in Fig. 1, lead loading on soil surfaces is extremely large compared to lead loading allowed on interior floors. Figure credit: Jennings AA. Analysis of worldwide regulatory guidance values for the most commonly regulated elemental surface soil contamination. *A.A. Jennings / Journal of Environmental Management 118 (2013) 72–95 Fig. 1, p. 82.* https://doi.org/10.1016/j.jenvman.2012.12.032.[56]

link between soil lead and children's health, the current U.S. soil lead standard is out dated.[58,59]

Margin of safety

Primary prevention is fraught with examples of policy lag. For example, the addition of fluoride to common products consumed by people in the water supply, dental products, salt, and many other sources was instituted in the 1950s to help prevent dental caries and bone fractures.[60] Some studies suggest, however, that neurotoxicity is associated with too much fluoride. The U.S. EPA initiated a study by the National Research Council to reevaluate acceptable fluoride levels. In 2006 the committee found that the previous *maximum contaminant level goal* (MCLG) should be lowered because of increased risk of neurotoxicity, tooth enamel fluorosis, and decreased ability to prevent bone fractures at this MCLG.[61] Despite these recommendations, fluoride continues to be added to drinking water and many commonly used products.

The U.S. EPA has published soil screening levels for lead to identify areas that may need further attention, if the land is on the National Priorities List for future use as residential land.[62] The U.S. EPA also has created lead abatement guidelines that are intended to guide owners of homes built before 1978, likely painted with lead-based paint, through the intervention process. A prominent piece of legislation, the Toxic Substances Control Act (TSCA), was enacted in the U.S. in 1976. The TSCA focused on addressing the production, use, and disposal of chemicals such as polychlorinated biphenyls (PCBs), asbestos, radon, and lead-based paint. This legislation mainly addressed future use and control of these substances and did not offer much information on intervention for already polluted areas.[63] Although the Clean Air Act of 1970 and the Clean Water Act of 1972 called for specific changes and regulation in the U.S., no significant legislation has been passed to extend the policies to contaminated soil. Moreover, the Stafford Act protects the U.S. EPA from legacy issues, allowing choice by agencies to follow or ignore governmental requirements for remediation of known soil hazards.[64] The U.S. must create more aggressive standards for soil to prevent exposure and protect children's health.

In contrast, other countries have moved forward with plans of informational surveys and action. In 1981, Norway created a program as a result of their Pollution Control Act that identified high-risk areas, explained the impact of the contamination, and provided instruction for intervention.[64] The Act provided guidelines for soil intervention and standards for cleanliness. The Norwegian Environment Agency (NEA) has identified sites that are confirmed or possibly contaminated based on proximity to landfills, factories, and other risk factors, and has been remediating these sites for decades.[65] Also, working with the Norwegian Geological Survey, the NEA introduced "Action Plans" in 2006 to reduce polluted soil in certain high-risk areas, focusing on child-care centers, elementary schools, and public parks. The NEA coordinated and funded the projects and guidance to prevent future contamination.[53] Rolf Tore Ottesen and Marianne Langedal shepherded the efforts in Norway that resulted in a major advancement for improving children's environmental health in the country.

Fig. 5 illustrates the remarkable reductions in blood lead of U.S. children. The reduction reflects the effectiveness of primary prevention policies focused on banning lead-based paint, removing lead from food containers, and banning lead in automotive gasoline. To continue progress in reducing blood lead requires shifting focus to residual sources of lead, such as the reservoir of lead dust in soil and lead dust potentially accessible on homes coated with lead-based paint. Research in New Orleans suggests that reducing lead in topsoil is effective in reducing children's blood lead.[58] Efforts are needed on several fronts to continue reducing children's exposure to lead.

The World Health Organization has identified a list of 10 chemicals of major public health concern and has recommended action to protect children and adults from the dangers of these chemicals. The United Nations has created Sustainable Development Goals that aim to "substantially decrease the number of deaths and illnesses from hazardous chemicals and air, water, and soil pollution and contamination; and achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment" by the year 2030.[66] Although these goals indicate a positive outlook worldwide, it is imperative that all nations continue to work towards compliance of these goals. One initiative toward improving children's health would be to decrease soil toxicants in communities where people live.[58]

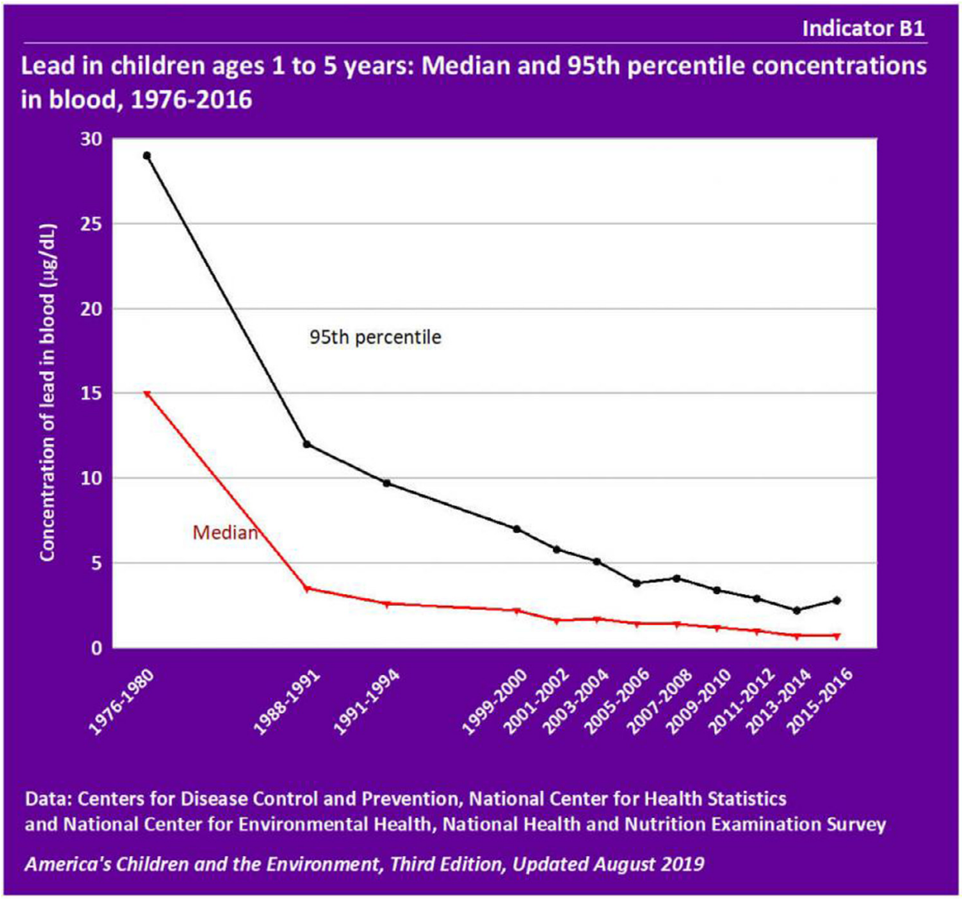

Fig. 5. Blood lead in U.S. children. Credit: United States Environmental Protection Agency. ACE: Biomonitoring - Lead. US EPA. https://doi.org/https://www.epa.gov/americaschildrenenvironment/ace-biomonitoring-lead. Accessed November 27, 2019.

Conclusions

Children are not simply small adults. They are not equivalent to adults in development, physiology, or maturity, and their health cannot be speculated on simply by extrapolating from adults. They require special consideration. The WHO defines vulnerability as "the degree to which a population, individual, or organization is unable to anticipate, cope with, resist and recover from the impacts of disasters."[67] Children, along with several susceptible groups, are vulnerable and it is the ethical responsibility of the current generation to work to protect children from the environmental health threats. Pediatric and adolescent clinicians and the healthcare community can work to prevent current and future children from being exposed to environmental toxicants. Along with other well-known environmental exposures from air and water, exposure to soil toxicants is an issue that must be addressed.

Declaration of competing interest

None of the authors have any conflicts of interest to disclose.

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