Confronting Legacy Lead in Soils in the United States: Community-engaged Researchers Doing Undone Science

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Abstract

Community-engaged soil testing projects fill gaps in an environmental regulatory system that does not meet the needs of people facing lead pollution in the United States. Lead has long been recognized as toxic, and soil is one source of lead exposure. However, in the U.S., systematic testing and monitoring of soil lead levels can be described as “undone science”—research in the public interest that is systematically neglected. Interviews with thirty community-engaged soil researchers across the country offer insights into the production and contestation of undone science surrounding soil lead. First, industrial interests resist the adoption of screening levels that offer higher levels of protection and environmental scrutiny. Second, the regulatory system focuses on legal action against identifiable polluters at industrial sites rather than broader actions to protect health. Third, soil testing is generally voluntary and there are deterrents to identifying contaminated soil. Fourth, while government programs for environmental testing are increasingly offloaded to academic researchers, research funding for “routine monitoring” is difficult to obtain. Fifth, straightforward exposure prevention is possible, but it requires funding and maintenance that devolve to individuals and households. Finally, the perceived lack of value or invisibility of soil may hinder public pressure on public agencies to direct research towards areas of undone science. Community-engaged researchers are challenging these mechanisms that produce undone science, creating new opportunities to protect health and the environment. The results of this study suggest that learning from community-engaged soil researchers could help to align lead mitigation policies with lived realities.

Keywords

Childhood lead poisoning, environmental regulation, soil contamination, soil lead, undone science, community-engaged research

Introduction

Lead (Pb) toxicity has been known since antiquity, yet it continues to impact public health, especially children (Coffey et al., 2020; Landrigan et al., 2018; Lin-Fu, 1992; Rees and Fuller, 2018). In this paper, we analyze lead governance in the United States, drawing on the knowledge and experiences of community-engaged researchers who focus on lead-contaminated soils. Much like citizen science projects dedicated to watersheds (Kinchy and Perry, 2011) or air quality monitoring (Harrison, 2011; Ottinger, 2010), community-engaged soil testing projects fill gaps in an environmental regulatory system that does not meet the needs of people facing pollution.

Lead causes a wide range of health problems, including damage to children's brains and nervous systems, miscarriages, high blood pressure, kidney problems, and other lasting harms (National Research Council, 1993; National Toxicology Program, 2012). In the U.S., public policy restricting lead use has produced substantial decreases in both child and adult blood lead levels (President's Task Force, 2016). However, historical lead dispersals into the environment are an enduring problem (Nriagu and Pacyna, 1988) that disproportionately harms Black children and children living below the poverty line (President's Task Force, 2016).

While attention to childhood lead poisoning emerged around lead-based paint in housing (Markowitz and Rosner, 2013; Warren, 2001), scientists working to address this public health issue have highlighted soil as another large reservoir of lead. A number of studies have demonstrated that lead dispersed into the environment accumulates in soils and dusts, which contribute to blood lead through ingestion and inhalation: "an almost inconceivable amount of lead potentially available to children" (Mielke and Reagan, 1998, p. 218; Cotter-Howells and Thornton, 1991; Datko-Williams et al., 2014; Filippelli and Laidlaw, 2010; Laidlaw et al., 2017; Landrigan and Baker, 1981; Lanphear et al., 1998; Mielke et al., 1983; Tong, 2000). Today, the Agency for Toxic Substances and Disease Registry (ATSDR), Centers for Disease Control and Prevention (CDC), Environmental Protection Agency (EPA), Department of Housing and Urban Development (HUD), and National Institutes of Health (NIH) all recognize soil and dust as potential sources of lead exposure for children (ATSDR, 2011; CDC, 2021; EPA, 2013; HUD, 2021; NIEHS, 2020).

Nevertheless, soils are generally neither tested nor monitored. As two scientists recently observed,

> there is no systematic program to map urban soil geochemistry and thus to identify and eliminate hot spots from this persistent and toxic pollutant. Indeed, we typically resort to analyzing maps of children's blood lead levels to find these particular pockets of high

> lead exposure—in other words, authorities wait until children are exposed so that we can find the source of the pollutant (Filippelli and Taylor, 2018, p. 3).[1]

The absence of research to identify lead contamination "hot spots" in soil is an example of what has been called "undone science" (Frickel et al., 2010; Hess, 2016). Calling it undone science goes beyond acknowledging what has yet to be done or what remains incomplete; instead, it:

> … draws attention to a kind of non-knowledge that is systematically produced through the unequal distribution of power in society, where reformers who advocate for a broad public interest find that the research that would support their views, or at least illuminate the epistemic claims that they wish to evaluate, is simply not there (Hess, 2015, p. 142).

In this case, the reformers advocating for the public interest are community-engaged soil researchers—like the scientists quoted above—who are advocating, through research, policy advocacy, and community-based interventions, for the reduction of soil lead exposures.

It is notable that the health implications of lead-laden soils are well established; the CDC states that lead-contaminated soil is a "hazardous source of lead exposure for young children" (CDC, 2021). However, lead detection and abatement in specific environments—the places where people live, play, garden, raise children, and so forth—remains to be done, and there are still contentious debates about the standards for lead in soil and needed regulatory interventions (*U.S. Court of Appeals,* 2021).

The absence of a systematic soil testing program leads to a variety of decentralized and uncoordinated initiatives. We identified over 50 such projects, programs, research groups, extension offices, and organizations across the U.S. [see Tables S1-S3]. [2] Many are

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[1] Reliance on children's blood lead testing is typical for housing inspections as well (Coffey et al., 2020).

[2] References cited in the introduction and projects listed in the supplementary material do not imply that an interview was conducted.

collaborations between communities and cross-disciplinary university researchers that engage parents, gardeners, and classrooms in analyzing soil (in some cases also plants, rainwater, and dust), and provide interpretation and guidance for low to no cost (Brown et al., 2016; Bugdalski et al., 2014; Cheng et al., 2015; Defoe et al., 2014; Fitch et al., 1996; Goswami and Rouff, 2020; Heiger-Bernays et al., 2010; Hunt et al., 2012; Johnson et al., 2016; Landes et al., 2019; Masri et al., 2020; McClintock, 2012; Ramirez-Andreotta et al., 2015; Schwarz et al., 2016; Sharma et al., 2015; Spliethoff et al., 2016; Tighe et al., 2020; Varelas et al., 2018). The projects are predominantly, but not exclusively, conducted in urban areas, and in the Northeast and Midwest. The size and scale of these projects vary widely. Some have been active for decades, measuring thousands of soil samples across an entire city or region and engaging in longstanding policy debates about lead, while others are more recent projects with a smaller number of participants and samples.

These researchers come from a broad set of disciplines, with formal and informal training in environmental (health) science, soil science, (geo)chemistry, geography, urban ecology, public health, science education, toxicology, law, film, science and technology studies, and community organizing. Some view themselves as traditional scientists working in support of communities, while others embrace more active roles in environmental justice organizing or policy advocacy. Their actions to protect health are various: mapping soils, correlating soil and blood lead, developing remediation techniques and best practices, informing regulations and public health guidance, and forming networks across community, academic, and regulatory circles.

We conducted in-depth semi-structured interviews, seeking to understand how community-engaged researchers are building research infrastructure to address what they identify as missing or undone research about lead exposure via soil. While there was considerable diversity among the people we interviewed, they converged on six main critiques of the way that soil lead issues are handled in the U.S. today, each of which has contributed to the systematic production of undone science. First, industrial interests resist the adoption of screening levels that would offer potentially higher levels of protection and environmental scrutiny. Second, addressing soil lead is hindered by a regulatory system that focuses on legal action against identifiable polluters at industrial sites, rather than broader actions to protect health. Third, testing and abatement are voluntary in most residential areas and there are deterrents to finding out whether soil is contaminated. Fourth, government programs for environmental testing have, in many cases, been outsourced to the academic research community; yet research funding for such "routine monitoring" is difficult to obtain. Fifth, straightforward exposure prevention is possible, but requires funding and maintenance, the costs of which have been devolved to individual households. Finally, the perceived lack of value or invisibility of soil may hinder public pressure on public agencies to direct research towards areas of undone science.

While addressing each of these mechanisms that produce undone science is daunting, in the case of soil lead, community-engaged researchers are challenging each one, creating new opportunities to protect health and the environment.

Soil Lead: Conceptual and Methodological Approach

The conceptual framework for this study comes from the sociology of science and the interdisciplinary field of science and technology studies (STS), which treat science and policy as intertwined and mutually constitutive. Regulatory institutions, for example, produce both scientific knowledge of contamination and the interventions meant to mitigate their impact. Gaps in policy (e.g., mandatory soil testing) lead to the systematic underproduction of knowledge (e.g., site specific soil lead data to prevent child exposure) (Frickel and Elliott, 2018; Frickel and Vincent, 2007; Kinchy et al., 2016). By the same token, ignorance about the extent of pollution can justify a dearth of relevant policy (Kleinman and Suryanarayanan, 2013; Richter et al., 2018). In the case of soil lead, a leading researcher on the effects of lead-contaminated soil on children's health recently wrote: "The U.S. has a Clean Air Act and Clean Water Act. The missing environmental component, soil, results in a knowledge gap that has a profound influence on the lives of children" (Mielke, 2015, p. 1).

As introduced above, such gaps form part of "undone science," a concept that sociologists of science use to describe the "systematic nonproduction of knowledge" shaped by an "institutional matrix of governments, industries, and social movements" (Frickel et al., 2010, p. 446). Undone science can be thought of as paths not taken in scientific inquiry, as well as neglect of particular topics, places, and communities. Undone science can result from knowledge suppression, as in cases of corporate and government secrecy (McGoey, 2019; Michaels, 2008; Oreskes and Conway, 2010; Proctor and Schiebinger, 2008). In the case of leaded gasoline—a major source of the lead found in soil today—some public health professionals of the 1920s saw tetraethyl lead as a grave health threat, but the research community was under "intense pressure" to understate the problem (Rosner and Markowitz, 1985). Decades passed before the health threats posed by leaded gasoline would again gain regulatory attention. While industrial suppression of inconvenient knowledge is an important cause of undone science, much research suggests that certain kinds of science are systematically ignored or left incomplete through the everyday practices of academic disciplines, regulatory procedures, and other dimensions of the "machineries of knowledge production" (Frickel and Vincent, 2007, p. 187). Everyday science practice can lead to a "mismatch" between the knowledge produced through science and what people external to scientific communities need to know to address problems in their lives (Frickel et al., 2009; Sarewitz and Pielke, 2007). Therefore, challengers may target both the intentional suppression of knowledge as well as the neglect built into regulatory systems and institutional science (Creager, 2021; Richter et al., 2021).

In the case of soil lead, challenges to undone science can take the form of lawsuits and policy advocacy, as well as community-engaged research. In this analysis, we focus on the latter. Based on our reading of publications by some of these researchers, as well as our own experiences working with gardeners to detect heavy metals (Engel-Di Mauro, 2020; Sandhaus et al., 2019), we expected that community-engaged soil researchers could offer insights about soil lead as a problem of undone science, as well as potential policy solutions. Our focus on community-engaged researchers is driven by a theoretical proposition that "mobilized counterpublics" (Hess, 2016) are the primary challengers to undone science, recognizing areas of research that would be valuable for achieving social change but are routinely ignored.

Community-engaged researchers have developed unique insights about environmental policy because they work at the boundary of academic science, environmental regulation, and affected communities, much like "boundary organizations" that understand the needs and values of multiple social worlds (Guston, 2001). They are not merely "issue advocates" or "honest brokers of policy alternatives"—two common portrayals of scientists involved in policy debates (Pielke, 2007). Rather, they are practitioners who derive expertise from both their scientific training and experiences working to make a difference in a "grassroots" capacity. Additionally, their efforts to prevent lead poisoning, often working outside of formal policy channels, provide insights about alternative means to address this public health challenge. For these reasons, in-depth interviews with community-engaged researchers can offer novel understandings about the contours of undone science and the reasons why it remains undone. Furthermore, their interventions suggest ways that community-engaged research challenges undone science and creates new possibilities for environmental health protection.

Literature and internet searches combined with snowball sampling revealed a small network of approximately 75 individuals involved in community-engaged soil research in the U.S. The analysis that follows is based on 30 in-depth semi-structured interviews from individuals across 12 U.S. states, with 20 at universities, 4 at government agencies, and 6 at community and nonprofit organizations.[3] We sought to cover the majority of projects we identified, reflecting the ranges of geographic distribution, disciplinary diversity, urban-rural positioning, and project age. Like any qualitative study based on a non-probability sample, this study has limited generalizability. We do not attempt to represent how all community-engaged soil researchers think about the problem of soil lead and its policy solutions, although during the coding process, similar ideas, experiences, and recommendations of who to interview next were repeatedly expressed, suggesting that we reached a point of data saturation to accurately address the research question (Saunders et al., 2018). Throughout this paper, we refer to our informants with pseudonyms.

This project was approved by the Rensselaer IRB and everyone interviewed gave informed consent. Interviews were conducted between March and June 2020 via video or telephone calls, lasting between 60 and 90 minutes. The semi-structured interviews were designed to be both *key informant* interviews (providing knowledge and interpretation of

[3] The research for this paper is part of a larger interdisciplinary project and two of the people interviewed are co-authors of this paper. Early in the collaboration, Walls interviewed Engel-Di Mauro and Ramírez-Andreotta because of their notable contributions to community-engaged soil research, using the interview guide developed for all interviews. After Kinchy and Walls analyzed the interviews and wrote a draft of this paper, Engel-Di Mauro and Ramírez-Andreotta contributed to review and editing.

situations that we were not able to observe directly) and *respondent* interviews (shedding light on individual motivations, experiences, and behaviors). Interviews were recorded and transcribed. Kinchy and Walls then analyzed the transcripts using qualitative data analysis software (Dedoose) and a combination of deductive and open coding. Deductive codes such as "access to soil testing" and "production of regulatory gaps" were created based on the literature about undone science and our preliminary understanding of this regulatory arena, while open coding was used to summarize emergent themes in the interviews. Subsequently, we sorted coded excerpts into broad categories, discussing several iterations until we arrived at an accurate representation of the full range of ideas. These categories are the themes discussed in detail below. We then synthesized the excerpts in each category to identify commonalities as well as differences in experience and opinion. In this effort, we elucidate how these community-based programs emerged, the obstacles they faced, and new opportunities they are creating within the environmental health field.

U.S. Case: Regulatory Frameworks and Community Science

Lead poisoning is an "ancient disease" (Lin-Fu, 1992, p. 24), but federal regulation of lead in the U.S. only emerged in the mid-twentieth century. Historically, lead was used in a wide variety of products—paint, gasoline, plumbing, food cans— and emitted into the environment through their manufacture, use and disposal, as well as through mining, smelting, waste incineration, combustion of fossil fuels, battery recycling, and other industrial processes (Nriagu and Pacyna, 1988). Despite cautionary warnings from some public health scientists, notably Alice Hamilton, in the 1920s, lead in paint and gasoline were unregulated in most of the twentieth century (Rosner and Markowitz, 1985; Warren, 2001). However, by the 1960s, growing public concern and community action regarding toxic chemicals (Sale, 1993), including lead (Fernández, 2020; Gioielli, 2010), combined with renewed scientific challenges (Patterson, 1965), spurred government action to curb lead entering the environment and consumer products (Markowitz and Rosner, 2013; Nriagu, 1998; Warren, 2001) [see Table 1]. The slow development of lead regulations in the U.S. stands in contrast with the precautionary principle, the idea that when an activity poses a combination of potential harm and scientific uncertainty, the proponent of an activity, rather than the public, should bear the burden of proof that harm will be avoided. It took decades of public pressure and scientist advocacy to establish this regulatory framework, and its gaps are still the subject of ongoing legal and grassroots struggles.

Table 1: Regulating lead entering the environment and consumer products in the U.S.

Medium	**First Regulation**	**Current Regulation**	**Agency: Legislative basis**
Paint (residential, decorative, and on children's products)	Contain <600 ppm (*Lead-Containing Paint*, 1977)	Contain <90 ppm (*Ban of Lead-Containing Paint*, 2008)	Consumer Product Safety Commission: Lead-Based Paint Poisoning Prevention Act (1971), Consumer Product Safety Act (1972) and Improvement Act (2008)
Gasoline (on-road vehicles)	Refinery-pooled average between leaded and unleaded gasoline <0.5 g/gal by January 1, 1979 (*Control of Lead Additives in Gasoline*, 1976)	Manufactured without lead additives, containing <0.05 g/gal (*Prohibition on Gasoline Containing Lead*, 1996)	Environmental Protection Agency: Clean Air Act (1963) and Amendments (1970; 1977; 1990), Motor Vehicle Air Pollution Control Act (1965), Air Quality Act of 1967 (1967)
Air (ambient)	<1.5 μg/m^3 (three-month time weighted average) (*National Primary and Secondary Ambient Air Quality Standards for Lead*, 1978)	<0.15 μg/m^3 (three-month time weighted average) (*National Ambient Air Quality Standards for Lead*, 2008)	
Air (workplace)	<50 μg/m^3 (eight-hour time weighted average) (*Occupational Exposure to Lead*, 1978)		Occupational Safety and Health Administration: Occupational Safety and Health Act (1970)
Public Water	<50 μg/l at entry point of water system (*National Interim Primary Drinking Water Regulations*, 1975)	<10% of water samples taken at first draw from customer taps can exceed 15 μg/l (*Lead and Copper Rule*, 1991)	Environmental Protection Agency: Safe Drinking Water Act (1974) and Amendments (1986), Reduction of Lead in Drinking Water Act (2011)
Plumbing	New plumbing must be "lead-free": solder and flux ≤0.2 wt. %, pipes and fittings ≤8.0 wt. % (*Lead and Copper Rule*, 1991)		
Foods, Drugs, and Cosmetics	Various regulations on contents, packaging, and labeling beginning in 1977 at 21 CFR Chapter I, including no lead solder allowed in food cans (*Lead-Soldered Food Cans*, 1995)		Food and Drug Administration: Federal Food, Drug, and Cosmetic Act (1938)

Mean blood lead levels decreased substantially with the enforcement of these regulations (President's Task Force, 2016). However, there are still children and adults with blood lead levels exceeding current CDC thresholds, particularly in urban and industrial areas and certain workplaces (Levin et al., 2021). One explanation for children's higher blood lead levels in those areas is the persistence and concentration of past uses of lead—notably leaded gasoline, deteriorated lead-based paint, and smelters—in those soils and dusts that require action to protect health (Mielke and Reagan, 1998). Additionally, deteriorated lead-based paint or other sources like munitions can contaminate soils and dusts outside cities and industrial areas.

Mounting public and scientific pressure around environmental contamination and lead poisoning contributed to two legislative mandates for EPA to address contaminated soils and dusts: the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA, or Superfund) (1980) and the Residential Lead-Based Paint Hazard Reduction Act of 1992 (Title X) (1992). It shares the latter mandate with HUD. Through Superfund, EPA established soil screening levels for individual contaminants that, if exceeded, *may* warrant additional investigation (EPA, 1996).[4] In practice, Superfund screens sites with a hazard ranking system and ultimately limits its attention to the most contaminated industrial sites (EPA, 1992). Title X addresses a broader distribution of lead, particularly in most housing and child-occupied facilities constructed prior to 1978 ("target housing") (*Lead-Based Paint Poisoning Prevention (EPA)*, 2019) [see Table 2]. EPA developed a "soil-lead hazard standard" using a combination of empirical, computational, and cost-benefit analyses. Their computational Integrated Exposure Uptake Biokinetic (IEUBK) model (White et al., 1998) predicts that if residential soil contains

[4] Similarly, individual state environmental programs have established screening values. Jennings (2013) showed that screening values can vary by an order of magnitude across agencies, with that of lead ranging from 50 to 500 mg/kg.

lead at the standard (400 mg/kg), then 5% of children will have blood lead levels that exceed 10 μg/dl, the CDC blood lead level of concern at the time of the initial rule (*Lead*, 2001). A third piece of legislation, the Small Business Liability Relief and Brownfields Revitalization Act (2002), amended Superfund to encourage voluntary cleanup and reuse of hazardous sites not on the National Priorities List.

As we will discuss in the remaining sections of this paper, under both Superfund and Title X rules promulgated by EPA, soil testing remains a voluntary initiative, except for federally owned and assisted target housing.[5] In this regulatory environment, community-engaged soil research has been essential for the detection of lead in many communities. Beyond filling knowledge gaps, community-engaged soil researchers are challenging the adequacy of current law and policy in their efforts to confront polluted soils. They question the scientific basis of the regulations on soil lead, their application, and their adequacy to protect health. In the remaining sections of this paper, we discuss these critiques and relate them to a broader understanding of the production of undone science, and its contestation.

Table 2: Definitions in the Residential Lead-Based Paint Rule

Term	**Definition**
Target housing	Housing constructed prior to 1978, except for the elderly, persons with disabilities, or 0-bedroom dwellings.
0-bedroom dwelling	Residence where living and sleeping areas are joined (efficiencies, studio apartments, dormitories, military barracks, and rentals of individual rooms in residences).
Lead-based paint	Paint or other surface coatings containing lead ≥1.0 mg/cm^2 or 0.5 wt. %.
Paint-lead hazard	Lead-based paint on a friction surface where the nearest horizontal surface underneath meets the dust-lead hazard; damaged or otherwise deteriorated lead-based paint inside or on the exterior of target housing or child-occupied facilities.
Dust-lead hazard	Surface dust in target housing or child-occupied facilities containing lead ≥10 μg/ft^2 on floors or ≥100 μg/ft^2 on interior window sills.
Soil-lead hazard	Bare soil on the property of target housing or child-occupied facilities containing total lead ≥400 mg/kg in play areas or average ≥1,200 mg/kg in yard.

[5] HUD requires assessment of lead-based paint hazards (including soil-lead hazards) and implementation of interim controls or abatement if hazard values are exceeded (*Lead-Based Paint Poisoning Prevention (HUD)*, 2019). However, *de jure* is not automatically *de facto* (Coffey et al., 2020).

Contested Screening Levels

The establishment of regulatory standards is often a contested dimension of environmental science and policy, particularly when the implicated industries resist the adoption of standards that would offer higher levels of public health protection and environmental scrutiny. In the case of soil lead, community-engaged researchers contend that current soil screening levels are insufficient, pointing especially to the EPA residential soil-lead standard under Title X (400 mg/kg).

In the ruling where EPA first established its residential lead hazard standards, their contested character is evident. EPA stated that the standards were "based on the best science available to the Agency," maintaining "its position that there is no known [blood] threshold for lead." However, lower standards for soil were not instituted. This decision was justified as stemming from a lack of scientific evidence of (1) health impacts at lower blood lead levels and, (2) reductions in soil lead causing subsequent reductions in blood lead (*Lead*, 2001). Critical public comments summarized in the ruling pointed to the absence of a margin of safety given this uncertainty and the EPA's own acknowledgement that no level of lead in blood is known to be safe, another failure to utilize the precautionary principle. The same critique arose in interviews; for instance, Bill, a university geographer, said regulators should use the pharmacological concept of a ten-fold safety factor to deal with variability between individuals when ingestion is a pathway of exposure.

EPA also provided justifications for these standards unrelated to health. These included concerns about insufficient resources to address problems in housing where lead levels exceed lower values, apathy and resignation of voluntary actors if the scale of lead contamination is perceived as insurmountable, and laboratory capability to measure lower levels of lead in blood and the environment. Public comments also claimed that costs associated with lower standards outweighed benefits (*Lead*, 2001). For example, Lutter (2001) argued that costs would exceed benefits if the residential soil-lead standard was below 5,000 mg/kg; this value is the equivalent of pulverized lead-based paint containing the minimum amount of lead defined by EPA and more than 6 times greater than the Superfund industrial soil screening level. In response to these justifications, Bill stated straightforwardly that the EPA residential soil-lead standard of 400 mg/kg "was created by the corporation" and "is guaranteed to be poisonous": "And I was at the table when it was done. They just said it's because of money, not because of people's health."

Many of our informants said that EPA is maintaining an inadequate standard in the face of new public health guidance and research. First, CDC instituted its current blood lead reference value (97.5th percentile blood lead level: 5 μg/dl) in 2012, which EPA has not yet incorporated into its rule. Paul, a regulatory toxicologist, stated that repeating the EPA's analysis with the current CDC value would indicate a standard of about 200 mg/kg, while Heidi, an earth scientist, had "heard talk of [EPA] trying to lower it to 200 [mg/kg] for years now."

Second, informants explained why the soil-lead standard should be lowered even further. Referring to research published in the last decade, Harry, a university soil scientist, stated that "if you analyze the data that are available for child exposure and lead levels in blood, you almost have to bring that level down to 100 [mg/kg] or lower." Michael, a university geochemist, told us that California's soil lead screening level is 80 mg/kg, set as a 90th-percentile estimate of a 1 μg/dl increase in the blood lead of a child (DTSC, 2019).

Inaction by EPA to update its rule has prompted two courses of action for community-engaged soil researchers. First, most advocate to their community partners that a precautionary approach is best, urging simple measures to avoid contact with soil that we will discuss later. Rather than targeting a particular soil-lead level for cleanup, general precautions are taken on the assumption that lead at any concentration is harmful.

Second, they have supported citizen petitions to EPA and lawsuits in the Ninth Circuit Court of Appeals to revisit the entirety of EPA's initial ruling (*U.S. Court of Appeals* 2017; 2018; 2021). In its first court-ordered revision, EPA lowered the dust-lead standards and left the soil-lead standard and definition of lead-based paint unchanged (*Lead-Based Paint Poisoning Prevention (EPA)*, 2019). Public comments on this revision from paint and lead industry associations--interest groups that have a long history of resisting regulation (Markowitz and Rosner, 2013; Rosner and Markowitz, 1985; Warren, 2001)--called for no changes. Subsequently, environmental advocates challenged the revised rule in a second lawsuit, demonstrating the sustained public pressure needed to obtain standards that protect health. The most recent court opinion states that EPA is "statutorily required [by Title X] to engage in the appropriate rulemaking to update the definition of lead-based paint and soil-lead hazard standards" (*U.S. Court of Appeals,* 2021, p. 12). These updates could increase the urgency to address lead contamination in communities where soil testing is implemented.

"Myopic" Focus on Identifying Responsible Parties

Even if more stringent soil screening levels are established, another concern is where and how they are applied. Community-engaged soil researchers highlight the ways that environmental policies based on legal action against identifiable polluters, like Superfund, draw focus to the most contaminated industrial sites, which does not match the broader extent of lead contamination.

Elizabeth, an environmental engineer with a long career in public health and the EPA, said that regulations were "just never designed or conceived" to address household and garden soils. She described EPA's regulations as mainly concerned with industrial processes and landfills, with the consequence that "there was never a focus on domestic soil in yards, for example, or in community gardens." This might pertain to yards and gardens given a specific industrial facility identified as causing the pollution, but, she said, "I never was aware of anyone interpreting soil regulations to apply for non-industrial neighborhoods, inner-city neighborhoods." Likewise, Paul noted that EPA is more successful at holding industries accountable when contamination is site- and source-specific.

Many informants expressed frustration that the environmental regulatory systems do not seem built to address the breadth and diffuse contribution of lead in soil. Nathasha, a university soil scientist, explained, "if you look at why [lead] is widespread, that is due to leaded gasoline usage." In contrast to specific industrial sites, "it's very hard for us to find someone to… clean it." Ray, a science education professor, specifically highlighted the limitations of Superfund for addressing widespread lead in soil. He indicated that Superfund focuses on "single sites that are hyper-contaminated," whereas:

> it's not necessarily those single sites all the time that we have to worry about. Because [lead] was in gasoline and because it was in paint, it's everywhere. And so I don't think that at the federal level, policy has accounted for that. It's better at dealing with the single sites, which are easier to identify and remediate.

Ray not only points out that Superfund does not direct funding toward lead that is "everywhere;" it also suggests that federal and state Superfunds are only doing the "easier" work, leaving more challenging tasks to voluntary action. Barbara, an environmental lawyer, echoed this sentiment when she indicated that the “complexity of identifying the source of these contaminants” makes it “time intensive and costly.” Further, she described the dominant regulatory approach for soil in the U.S. as “myopic,” explaining that problem-solving has been “tied to holding someone responsible instead of tied to protecting the health of a community.” Consequently, community-engaged soil researchers have developed proactive projects with their partners to start addressing the broader scale of soil lead and suggested reinstating the lapsed Superfund tax to cleanup Superfund sites with no identified polluter and the broader scale of pollution.

Voluntary and Indirect Screening

The more challenging task of addressing the diffuse nature of lead is generally taken on a voluntary basis by homeowners, renters, gardeners, and other concerned individuals. While community-engaged soil testing programs help fill knowledge gaps and HUD requires lead assessments of federally owned and assisted housing, the people we interviewed described a need for much more significant investments in soil lead detection.

Instead of testing children’s environments, lead poisoning prevention programs commonly rely on children’s blood testing. Nearly every informant said that while children’s blood testing is an important backstop, using children as proxies for environmental contamination was both immoral (uses children as lead detectors) and ineffective (inherently allows exposure). Dorothy, a university chemist, highlighted that even blood testing is incomplete:

> Like many parts of the country, in [Dorothy’s state], children are not required to get a blood lead test at age 12 and 24 months, which is what the CDC recommends. Even kids who are on Medicare who are supposed to be tested, and it’s free for those kids, a lot of

them are not getting tested. So not only do we have an immoral way to detect lead, but it doesn't even work very well.

Respondents described the unenforceable and voluntary character of soil screening levels, including the absence of a plan to meet them. Linda, a university urban ecologist, questioned whether "having a lower threshold necessarily translates into having a better outcome… if they're not necessarily enforced or there's no action associated." Dorothy stated that "there isn't a systematic effort to find out what the problem is… you can't measure it, you can't monitor it, you can't regulate it." Finding out about even the possibility of soil lead is not easy. For example, Maria, an environmental advocate, told us that in community gardens, it takes a "motivated gardener… someone who prioritizes [soil lead] enough to speak to other people that come to the garden."

Local agencies may be reluctant to initiate systematic soil testing because they lack resources to follow through with exposure prevention. Marc, a university soil scientist, stated that his city's officials have responded to his inquiries about soil testing in public places by asking "Why would we do that?" Without federal support, such as from HUD, he believes cities will be reluctant to test soil and take on responsibility for identified contamination. Chris, a university earth scientist, said that his city tests tap water for lead, but officials balked at his suggestion of testing soil. While we had fewer interviews with scientists working within state and local agencies, one public health professional at a state health department, William, said that his agency funds community gardening initiatives, but has no programmatic responsibilities for soil contamination in gardens. He collaborated with university researchers to obtain external grants and conduct soil testing. These examples suggest that state and local agencies are not well supported in carrying out soil lead exposure prevention, even if they wanted to do it.

The absence of support for mitigation efforts also deters individuals from voluntarily testing soil. As Michael told us, if sufficient resources are not available to act on knowledge of soil lead, even motivated individuals may fear testing: homeowners may fear reductions in property values and the inability to relocate, renters may face eviction if they raise concerns to landlords, and community gardens, parks, and playgrounds may face closure by municipalities. In this context, community-engaged soil researchers have attempted to advocate for and obtain resources to both produce this knowledge and act on it, as we discuss below.

Insufficient Funding for Soil Testing Services

Informants also described reduced or no spending on soil testing services in local, state, and federal agencies. In many cases, the academic research community has picked up the burden of funding and providing soil testing.

Informants spoke of soil testing programs that have lost funding. For example, ATSDR and EPA started soilSHOP, a program at health fairs where people can bring soil samples for rapid lead testing. A few of the scientists we interviewed had previously participated in or hosted a soilSHOP in their communities. Alicia, a university environmental health scientist, explained that, due to diminished funding, a host now needs to supply an x-ray fluorescence spectrometer ($30,000+) and advertisement funds. Elizabeth told us about Environmental Monitoring for Public Access and Community Tracking (EMPACT), an EPA program that supported the Lead-Safe Yard Project in two Boston neighborhoods during 1998-99. The project involved homeowners to test their yards and address any lead found, and produced a detailed manual for initiating similar projects elsewhere; however, federal support and the EMPACT program ended. Likewise, Betty, a university geochemist, said that her city stopped its lead testing program when a grant expired, giving her laboratory its disused analysis equipment.

Foundations, both local and national (such as the Robert Wood Johnson Foundation), have provided some support to community-engaged researchers filling gaps in soil lead detection. For instance, Dorothy said her team has relied on foundations and internal university grants to establish their community-engaged soil research. Her university supports her work because she frames it as community outreach. Some university researchers manage by piggy backing their soil lead work off other laboratory projects or building it into undergraduate curriculum.

However, public research funding for soil testing is limited, and several informants indicated that federal funding agencies were uninterested in supporting projects that focused on lead detection. Reviewers and program officers tend to see soil testing as "applied" research rather than producing new knowledge. Alicia explained how she navigated that obstacle when studying arsenic, another soil contaminant:

> [A federal agency] program officer said, "well, you're proposing to work with arsenic, we already know a lot about that, so I don't know if that's worth it." … Luckily I'm stubborn and … I searched and so much research being funded on arsenic with the connection to obesity, its connection to diabetes, cancer causing, lung cancer. … So I think the trick is to do both. I will do community-based citizen science work, but then in the lab, I'll do the bioaccessibility studies or I'll do comprehensive exposure assessment… You do additional analyses to add more value to it.

Harry and Sally, two soil scientists at a university, echoed this sentiment of connecting soil testing and health outcomes in assembling a competitive grant application.

Some informants noted that traditional science funding programs are not designed to support community-engaged research. Linda noted that the federal funding structure does not allow for co-created research questions that emerge from working with communities. Funding shortfalls also limit the possibility of compensating community partners. Sam, a university geographer, mentioned his desire yet inability to pay his non-academic collaborators. Antonio was uncomfortable that people facing environmental contamination were recruited as volunteer labor on soil testing projects. He highlighted the need for funding to pay or give in-kind compensation.

In the absence of public soil testing services, some academic researchers are attempting to meet that need. However, existing funding models for academic scientists do not often match the collaborative design of these projects.

The Need for Affordable Exposure Prevention

Our interviews suggest that the undone science of soil lead goes beyond gaps in detection; there is also a need for innovation and investment in exposure prevention strategies. Most of the people we interviewed sought to prevent soil lead exposures by experimenting with and advocating for a range of remediation and mitigation options. As predicted, in the absence of both a precautionary approach and systemic testing program, the costs of preventing lead exposure devolve to concerned individuals, so there is a need for simple, affordable, and durable interventions.

According to the people we interviewed, EPA has not met the broad scale of lead dispersed into the environment through Superfund and Title X. During the Superfund process, EPA conducts remedial investigations to determine the nature and extent of contamination, using its hazard ranking system to determine if the degree of contamination at a site meets the criteria to become a Superfund site (1992). One approach to remediation at Superfund sites is to remove contaminated soil and bring in “clean soil” to reduce exposure in impacted residential areas.

Typically, or at least until the Remedial Design/Remedial Action stage (EPA, 2015a), designated contaminated areas are fenced off and in situ remediation strategies are employed (e.g., natural attenuation, physical barriers, soil capping or application of a soil sealant) to keep contamination in place and avoid (further) dispersal (EPA, 2015b). Informants generally agreed that excavation is not a sustainable option based on the widespread distribution of lead and the additional environmental degradation involved. Second, its high financial cost coupled with the EPA mechanism for funding cleanups--litigation against polluters--often produces inaction. Furthermore, due to atmospheric deposition, soils can be re-contaminated over time, especially in urban areas, meaning ongoing monitoring and maintenance are necessary and additional remediation efforts may be needed over time and at a neighborhood-wide scale (Clark et al., 2008). Thus, the people we interviewed discussed several alternative strategies for reducing soil lead exposures, primarily focusing on creating physical barriers to contain contaminated soils.

Informants highlighted some cities that were making notable interventions. Bo, a university geochemist, and Kira, a university environmental scientist, told us about the Clean Soil Bank in New York City that mixes glacial sediments excavated during construction projects and composts to construct soils for gardening. In New Orleans, Mississippi River alluvium has been used to cover soil lead as well. Helen, a university soil scientist, cited Tacoma, Washington:

> There was an ASARCO [American Smelting and Refining Company] smelter… and so there is extensive lead and arsenic contamination in the soils. A portion of the city was a Superfund site. At this point, they have a very active community garden program. The wastewater treatment division manages a lot of it and what they'll do is free soil sampling at the community garden; soil testing. And then they'll also provide yard waste compost. Biosolids-based potting soil, free of charge, to all community gardens. They provide

> materials to build raised beds. They also have diverted large amounts of cardboard from the solid waste stream, and they use that as a barrier to soils between the raised beds. And they have also diverted wood waste and chipped it, and the mulch is provided to put on top of the cardboard… That's an area where lead and arsenic were gigantic issues and now are non-issues.

Some people recommended that urban residents cover soil even without testing. For instance, Michael noted that soil lead concentrations likely increase when approaching city centers and under building driplines. Some childcare facilities in his city used mulch to cover soil based on these criteria alone. Other physical barriers include geotextiles, cardboard, gravel, new soil, and vegetation. Additionally, designated play areas and raised gardens can be built away from buildings. Bill suggested that cities reluctant to confront soil contamination could be persuaded to invest in "greening" initiatives, such as introducing new layers of soil and improving soil quality for planting trees and gardens. This may be an effective way to contain contaminated soils without provoking resistance from city leaders who do not want lead contamination to be publicized.

While preventing exposure to soil lead is possible with these kinds of interventions, Michael emphasized that the scale of the problem has not been met with a proportionate amount of funding, calling for policy to create "a bigger pie" to protect children's health. Likewise, Elizabeth and Susan, a public health scholar, suggested that a long-term sustaining fund is required for making and maintaining lead-safe neighborhoods in the presence of lead. Ongoing monitoring and maintenance are necessary to ensure that people and spaces remain safe from future incursions of lead from deteriorating lead-based paint, wind-blown soil and dust, and potential new sources.

Disregard for Urban Soils

Public pressure has been paramount in establishing and improving environmental regulations and directing research toward areas of undone science. The people we interviewed work to make urban soils visible and recognizable as a local resource (more than simply "dirt") in partnership with other collective actions like community gardens, urban greening efforts, and environmental art. Their accounts suggest that one of the reasons why urban soil testing may remain undone is that soil in cities is culturally invisible.

Bo told us that the dominant perception of urban soil as waste rather than resource only began to shift recently with emergent urban gardening, urban ecology and unexpected biodiversity, stormwater management, and climate change mitigation and adaptation. Charles, a soil scientist, stated that the first urban soil survey in the U.S. was carried out in Washington, DC (USDA, 1976). According to him, the formation of an urban soils team at the U.S. Department of Agriculture and more recent urban soil surveys (e.g., New York City (Shaw et al., 2018) reflect that shift. However, the historic focus on rural areas and agricultural production has left many open questions specific to other soils. According to Antonio, there is no sufficient soil classification scheme for urban soils.

Informants envisioned other ways of cultivating appreciation for soils and their complexity, including art, science curriculum, and caretaking. Other studies have shown the importance of art in transforming human-soil relations (Puig de la Bellacasa, 2019) and that gardening and contact with soil can provide general positive feelings and therapeutic outcomes, such as alleviating stress (Ramirez-Andreotta et al., 2019). Linda and Betty each pointed to Artist Mel Chin's Operation Paydirt/Fundred Dollar Bill Project on lead poisoning (2006).

Another artistic intervention noted in interviews was Residency Unlimited's "Dirt & Debt" program, where artists explored healthy, accessible soil as central to thriving societies (2019).

Engaging school students and designing science curriculum was a point of emphasis for some informants. Ray told us that:

> Our school curriculum is not organized around what matters in our lives and our communities and our society… We learn about the periodic table of the elements, and we learn to balance equations, but we don't learn why any of it matters. And we don't learn about the real scientific issues that are happening in our lives.

His work brings soil lead into science classrooms with community activists and university scientists as partners. Similarly, Charles has partnered with community organizations to speak with grade school students about local environmental concerns. Linda shows her introductory university students the PBS movie "DIRT!" to bring soil into the curriculum, while others engage their college students in research about soil and environmental justice in their communities. Some community-engaged soil researchers have developed soil testing programs involving students in middle and high school, including Sue and Tim, and Anna and Tom, two pairs of environmental justice advocates.

Consistent with other recent studies of soil scientists and farmers (Krzywoszynska, 2019; Puig de la Bellacasa, 2019) some informants viewed soil testing and remediation as continual acts of maintenance and caretaking that stimulate connections with soils, between environmental and human health, and among people. Kira saw creating new layers of healthy soil as a continuation of geological processes that produce stratified layers and historical record of industrial contamination. Frances, an environmental justice advocate, viewed soil testing as community organizing by connecting industrial activity and community health. Antonio highlighted gardens as sites of intergenerational learning and cultural transfer, something limited in school classrooms according to Ray. Networks also emerged around their work; the Legacy Lead Network in New York City, the Metal Redlining Network across several Midwestern Universities, and the international Soils of Urban, Industrial, Traffic, Mining and Military Areas Conference are three examples.

These perspectives suggest that confronting undone science involves not only doing research, but also changing cultural perceptions and building relationships with soil to confront contamination and a history of regulatory neglect.

Conclusion

In the U.S., community-engaged researchers have built programs and infrastructure to support the detection of lead-contaminated soil and subsequent actions to prevent exposures. These projects “disturb the regime of imperception” around soil lead (Murphy, 2006; Richter et al., 2021, p. 646), making contamination visible both to the people who submit soil for testing and to the wider community of researchers and activists working to reduce lead poisoning. Because these researchers frequently step out of conventional roles and confront the challenge of soil lead from the points of view of their community partners, they provide valuable insight about the state of science and policy as it affects people living in lead-contaminated places.

One clear lesson we can draw from these interviews is that further reducing lead exposures in the U.S. will require a change in strategy, because existing frameworks (such as targeting identifiable polluters and setting voluntary screening standards) are poorly aligned with lived realities. Community-engaged researchers described multiple angles of necessary intervention: setting more protective screening levels, creating systematic soil testing and monitoring programs, providing testing services to individuals, funding and assisting with exposure prevention (e.g., creating lead-safe yards), and changing perceptions of human relations with soil. Many examples of community-engaged soil research pursue these interventions; however, as the people we interviewed readily attested, the scale of the problem far exceeds what they can accomplish. Community-engaged soil researchers remain poorly funded and marginal to decision-making processes, and the problems with the regulatory system that they describe go far beyond the specific case of lead.

Thus, questions remain about how to most effectively change policy at the local, state, and federal levels to bring about widespread changes in lead exposure prevention strategy. Our observations suggest that enhancing support for community-engaged research programs—whether funded by universities, cities, state agencies, private foundations, or the federal government—will not only increase capacity for lead detection in particular communities; it will also build a larger community of experts who can advocate for changes to standards, policies, and practices based on lived experiences. This could create a feedback loop, as a growing number of people become invested in advocating for lead exposure prevention initiatives that, in turn, further strengthen this "mobilized counterpublic." However, more research is needed to trace the broader effects of these localized programs on politics and policy.

This case study raises broader questions about the dynamics of undone science. It is striking that there has been a century-long conflict between advocates for lead exposure prevention and defenders of the lead and lead-related industries. What sustains mobilized counterpublics over such prolonged struggles, and how do new generations of concerned scientists reframe undone science in new historical contexts? Another question pertains to community-university relations: What are the resources that enable community-engaged research to occur, and how might this relate to the broader forces affecting science and education in the

U.S. today? For instance, while it is frequently observed that academic science has taken a turn toward commercialization, the projects that we examined appear to represent a countervailing shift toward public service. How widespread are such projects (beyond soil lead studies) and what are the factors supporting their emergence? We hope that the example of community-engaged soil research will prompt further research on these dynamic relationships between science, policy, and social movements.

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