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PRACTICE BRIDGE

Applying a novel systems approach to address systemic environmental injustices: Constructing soil for limiting the legacy of lead (Pb)

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The knowledge of unsustainable human and Earth system interactions is widespread, especially in light of systemic environmental injustices. Systems science has enabled complex and rigorous understandings of human and Earth system dynamics, particularly relating to pollution of Earth's land, water, air, and organisms. Given that many of these systems are not functioning sustainably or optimally, how might this field enable both rigorous understanding of the issues and experiments aimed at alternative outcomes? Here, we put forth a novel, multiscale systems science approach with three steps: (1) understanding the systemic issues at hand, (2) identifying systemic interventions, and (3) applying experiments to study the efficacy of such interventions. We illustrate this framework through the ubiquitous and yet frequently underrecognized issue of soil lead (Pb). First, we describe the systemic interactions of humans and soil Pb at micro-, meso-, and macroscales in time and space. We then discuss interventions for mitigating soil Pb exposure at each scale. Finally, we provide examples of applied and participatory experiments to mitigate exposure at different scales currently being conducted in New York City, NY, USA. We put forth this framework to be flexibly applied to contamination issues in other regions and to other pressing environmental issues of our time.

Keywords: System science, Social-ecological systems (SES), Anthropocene, Lead contamination, Soil remediation, Environmental justice

1. Introduction

Understanding, predicting, and responding to rapidly changing processes on Earth's surface is among "the most pressing challenges of our time" (Harden et al., 2014). We propose that there is a viable and valuable role for research to play in efforts aimed at environmental remediation and environmental justice (EJ) and that systems science approaches are key to such endeavors. Here, we put forth a novel, multiscale systems science approach with three steps: (1) understanding the systemic issues at hand, (2) identifying systemic interventions, and (3) applying experiments to study the efficacy of such systemic interventions. This systems approach is informed by the work of numerous scholars and researchers who have laid the foundation for understanding multiscalar, nonlinear complexity in dynamic coupled systems (see Von Bertalanffy, 1972; Meadows, 2008; Ostrom, 2009). We will begin by situating this discussion in emerging discourses of human and nonhuman system interactions at micro-, meso-, and macroscales, but we will not directly apply any of these previously articulated frameworks. Instead, we seek to build on the work of others to illustrate three aspects of our novel approach using lead (Pb) in urban soil as an example.

A systems approach is well-suited to address issues revolving around Pb, a notorious chemical element, lead has been mined for at least 8,000 years (Pompeani et al., 2013), and its deleterious health effects have been recorded for at least the past 2,000 (Hernberg, 2000). Lead use peaked in the 1970s with the use of tetraethyl lead additives in gasoline and leaded paint and precipitously declined as a result of federal regulations (Needleman, 2000). In many ways, the reductions of Pb exposure have been one of the great environmental and public health successes of our time (Settle and Patterson, 1980). And yet,

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a variety of processes including mining, smelting, and refining as well as incineration, the peeling of paint, and emissions of leaded gasoline have left a legacy of this element in soils (Alloway, 2013).

This legacy of lead in soils is invisible. But over the past four decades, researchers began to identify and map soil Pb, first in Baltimore, MD (Mielke et al., 1983), then Minneapolis, MN (Mielke et al., 1984), and New Orleans, LA (Mielke et al., 2013), and now, hundreds of peer-reviewed articles in regions throughout the world have been published documenting this nearly ubiquitous occurrence (i.e., Meuser, 2010; Datko-Williams et al., 2014). Yet the links between soil Pb and blood Pb (i.e., human health impacts) have not yet been sufficiently accepted by regulatory agencies. Many of the major Pb exposure sources have been reduced for the general population, with major blood lead level (BLL) declines occurring between 1976 and 1991 after the removal of 99.8% of Pb from gasoline and removal from Pb in soldered cans (Pirkle et al., 1994). Despite monumental BLL declines and efforts pursued for primary prevention, far too many children continue to be poisoned by Pb throughout the world. In New York City (NYC) in 2018, for example, 351,486 children were tested for blood Pb, and 4,717 of them had levels greater than 5 μg/dL (NYC Department of Health, 2020). Lanphear et al. (2018) found elevated BLL to account for 412,000 deaths annually. Burdens of Pb exposure, as with many environmental hazards, have historically fallen on and continue to disproportionately expose communities of color and low-income populations in the United States and worldwide (Sampson and Winter, 2016; O'Connor et al., 2020).

We call attention to this urgent issue of environmental injustice and employ a systems approach to understand the interactions between humans and soil Pb at multiple scales, to identify the interventions that have been aimed at limiting exposure, and to inform applied experiments for continuing to protect public health. This approach has already enabled a number of experiments on systemic interventions to limit soil Pb exposure, and we suggest that it can be flexibly adapted to address other pressing social and ecological issues of our time.

2. Why systems?

A systems perspective enables rigorous, dynamic, multidisciplinary, and multiscalar approaches to be used to address challenging problems (Odum, 1983). A system is defined as "a set of elements or parts that is coherently organized and interconnected in a pattern or structure that produces a characteristic set of behaviors, often classified as its 'function' or 'purpose'" (Meadows, 2008, p. 187). A system is "more than the sum of its parts" and contains stocks, which are the "memory of the history of changing flows within the system." Systems also contain feedback loops, which are chains of "causal connections from a stock, through a set of decisions or rules or physical laws or actions that are dependent on the level of the stock, and back again through a flow to change the stock" (Meadows, 2008, p. 188).

2.1. Global scale systems theory: The inequitable Anthropocene

Although general systems theories can be applied to virtually any field of study (Von Bertalanffy, 1972), here we focus on multiple scales of human system interactions with nonhuman systems. On the macroscale, this work is situated within Earth Systems Science, a field which has begun to articulate ways in which humans act as a geologic force (Thomas, 1956; Vitousek et al., 1997; Crutzen, 2002; Ruddiman et al., 2015; Waters et al., 2016; Waters et al., 2018). Although living creatures have frequently played important roles in shaping Earth systems (i.e., photosynthetic bacteria have been oxygenating the atmosphere for at least 3.5 billion years, Blankenship, 1992), our species clearly exerts a tremendous impact on the material and energetic cycles around us. The concept of the Anthropocene as a geologic epoch characterized by human action supports an expansion of spatial and extrabiological perception. Seeing our species as a geologic force enables us to recognize that the ecological and environmental issues we face are not just impacting charismatic megafauna and local waterways (Syvitski and Kettner, 2011; Brown et al., 2017). The matter and energy we move is occurring on and can be quantified at global scales and calls for us to consider our effects on nonliving Earth elements (Gaffney and Steffen, 2017). The Anthropocene idea also supports a dynamic tension between temporal scales. Earth systems have been forming for 4.6 billion years, and in a mere 10,000 years or less, collective human impacts are having tangible effects. Finally, the Anthropocene idea may help humans to recognize that while all living creatures interact with their environments, human consciousness allows for highly informed and creative responses (Graham and Roelvink, 2010; Gibson-Graham, 2011; Holm et al., 2013; Palsson et al., 2013; Steffen et al., 2018).

This consciousness also fosters recognition that certain groups of people, namely those with more access to structural power, have been primarily responsible for creating the conditions of the Anthropocene and have accumulated material wealth through the extraction and movement of matter and energy throughout Earth systems (Clark and Yusoff, 2017; Yusoff, 2018). People with less access to structural power are less responsible as drivers of change in the Anthropocene and have borne disproportionate burdens of displacement and marginalization, particularly in the form of environmental racism (Bullard, 1993; Cole and Foster, 2000; Pulido, 2000; Holifield, 2001). Systemic racism has been shown to drive ecological and evolutionary outcomes, particularly in urbanized landscapes (Schell et al., 2020). Attention to our species' roles within Earth systems and the inequitable responsibilities and burdens placed on differently identified people are essential components of the systems framework outlined here.

2.2. Social-ecological systems (SES) theory: Nonlinear dynamics and thresholds

On a relatively smaller temporal and spatial scale, we look to SES to inform this framework, defined as "complex adaptive systems where social and biophysical agents are

interacting at multiple temporal and spatial scales" (Janssen and Ostrom, 2006). Research in this field examines coupled human and natural systems and articulates complex patterns and processes that would not be captured by social or natural science separately. Liu et al. (2007) synthesize case studies from around the world with couplings that vary across temporal, spatial, and organizational scales and highlight the importance of attending to "nonlinear dynamics with thresholds, reciprocal feedback loops, time lags, resilience, heterogeneity, and surprises" within these areas of inquiry. Such frameworks have been applied toward understanding ways in which humans act as geologic agents on specific landscapes and how temporal lags impact landscape restoration efforts (Kondolf and Podolak, 2014). The emerging science of human-landscape systems recognizes the inextricable interactions between hydrogeomorphological, ecological, and human processes and functions (Harden et al., 2014). Work in this field calls for a range of physical, biological, and social research to contribute to such integrative science to both rigorously understand human and nonhuman system interactions while also attending to ways in which humans are shaped by such interactions (Chin et al., 2014).

Ostrom's (2009) framework for understanding the sustainability of SES outlines constituent subsystem entities as well as their interactive links. This framework has not yet been applied to interactions around soil Pb, and while this would be a productive area of inquiry, here we focus on soil less as a resource from which value can be extracted and more as an actor embedded in a range of enmeshed dynamics (see Latour, 2005). Ostrom's framework may also be used to identify potential SES vulnerability and susceptibility to disturbance (Anderies et al., 2004). Systemic disturbance is frequently viewed as problematic, but certain disturbances, as will be discussed here, can be seen as interventions aimed at shifting systemic outputs. In the case of soil Pb exposure, such a shift is desirable. In other situations, where a system is not functioning in alignment with sustainable outputs (i.e., excessive deforestation, depletion of aquifers, climate change, or any other form of pollution), the forthcoming framework centralizing disturbances as desired interventions may be of particular value.

2.3. Paradigm shifts: Urban systems science and coproduction of knowledge

Social and human coupling with nonhuman systems can be focused to consider a more specific urban systems science (Groffman et al., 2017). These authors propose an approach to interdisciplinary and transdisciplinary research for advancing sustainability science in cities in a number of ways, including an emphasis on human values and concerns that shape the structure and function of urban ecosystems, coproduction of knowledge with stakeholders that considers their values and perceptions (even when they are at odds with scientific understandings), and working with experts in a variety of disciplines to address fundamental questions about broad issues of sustainability (Cornell et al., 2013; Childers et al., 2014). This urban system science would include the voices and perspectives of low-income communities and communities of color as essential for driving the production of new knowledge (Torre et al., 2012). We draw from the field of Critical Participatory Action Research (CPAR), which contends that all people, and particularly those who have been historically marginalized, have a right to both understand and produce new knowledge as research (Appadurai, 2006). We find that biogeochemical-social/SES research can be in alignment with CPAR methodologies that in the words of Fine (2018) enable a "critical analytic gaze to the social arrangements, institutions, distributions, ideologies, and social relations that reproduce and legitimate everyday injustice" (p. 7).

We situate this work within an ontological orientation of various scales of human and nonhuman system interactions, an epistemological focus on urban systems and coproduction of knowledge with experts outside of academia, and a methodological emphasis on applied experimentation. Although most biological, chemical, and physical sciences demonstrate a strong preference for basic science research (Cornell et al., 2013), we contend that the rigorous concepts and methodologies of basic science can be applied to experiments on systemic levels in order to understand not just what processes are already occurring but also to generate data on what outcomes may arise from a range of interventions. Just as systems-based understandings should lend themselves to adaptive management and governance (Walker et al., 2004), we argue that such adaptations should be empirically studied. Governance is an essential component of SES dynamics and change (Janssen and Ostrom, 2006) and opportunities for research to support such sustainable outcomes are widespread (DeFries et al., 2012), but implemented programs and policies are not generally viewed as experiments (even though they may be experimental in nature). When solutions do not produce desired outcomes, they may be seen as failures. Were they conducted as experiments, however, the failures could be identified as useful data, enabling revisions for subsequent experiments, and "serendipitous science" (Gallagher et al., 2020). Thus, this framework looks to applied systemic experimentation as a crucial component for consideration of system governance.

In this vein, we agree with Grove et al. (2015) who assert that the perceived dichotomy between basic and applied sciences need not be at odds. These authors cite Stokes (1997) in articulating a synthesis between these fields as "use-inspired basic research," which they describe as a "science designed to enhance fundamental knowledge while also addressing a practical concern." We articulate an applied and participatory systems research framework that utilizes the following three steps:

1. Conceptualize human and nonhuman system interactions at multiple scales.
2. Identify interventions toward desired systemic outputs.
3. Conduct applied and participatory experiments to study effects of interventions.

In the discussion to follow, each of these steps will be applied to the issue of soil Pb contamination. First, a system of human and soil Pb interactions will be conceptualized at micro-, meso-, and macroscales in time and space. Interventions for mitigating soil Pb exposure at each scale will then be discussed. Finally, we will provide examples of applied and participatory experiments to mitigate soil Pb exposure at different scales that are based on this systems framework and are currently being conducted in NYC, NY, USA.

3. Conceptualizing a system of soil lead

Out of all the potentially toxic elements and compounds humans have concentrated in urban soils, Pb is the most common, having been identified in soils in virtually all corners of the globe (Delbecque and Verdoodt, 2016; Marx et al., 2016). It is not only one of the most common toxic elements found; it is also listed as the number two priority toxic substance by the Agency of Toxic Substances and Disease Registry (Agency of Toxic Substances and Disease Registry [ATSDR], 2020). There is a tremendous reservoir of soil Pb, due to the legacies of industrial activities, leaded paint dust, and leaded gasoline emissions (Mielke, 2016). Although much attention has been given to mitigating Pb exposure from indoor paint and water, soil Pb is underrecognized as an important exposure pathway (Mielke, 2015).

Exposure to the stock of Pb in soil, or any media, may produce seriously adverse health impacts. Pb is a neurotoxin with lifelong and potentially fatal effects (Bellinger, 2011), and the EJ issues associated with exposure in various media such as buildings, paint, occupations, and water are well known (Dudka and Adriano, 1997; Stretesky, 2003; Clark et al., 2006; Pokras and Kneeland, 2008). The presence of Pb in soil as a major risk for exposure has been articulated by researchers but has not been accepted by many regulatory agencies (Mielke et al., 1983; Mielke, 2015; Laidlaw et al., 2017). Similar to the geographic patterning of Pb in other media, soil Pb exposure is an EJ issue, with concentrations found to be higher in low-income communities and communities of color (Filippelli and Laidlaw, 2010; McClintock, 2012; Mielke et al., 2013; Cheng et al., 2015; Filippelli et al., 2015; Laidlaw et al., 2016).

It is important to acknowledge that humans are not the only organisms whose health is adversely impacted by Pb. Indeed, microbes, plants, and fish (Demayo et al., 1982; Rabitto et al., 2005), birds (Friend, 2009; Mateo et al., 2014), crocodiles (Twining et al., 1999), rats (Nakayama et al., 2011), boars and deer (Rodríguez-Estival et al., 2013), sheep (Pareja-Carrera et al., 2014), and many other living creatures (Nriagu, 1990; Meador, 1996) have been harmed by high Pb concentrations at Earth's surface. Researchers have traced the exposure pathways of Pb for these organisms through water, the atmosphere, and also in soil. The framework to be discussed here could be applied to any of these organisms on Earth. In the vein of anthropocentrism, we focus this discussion on the impacts of Pb on humans.

Whether they were motivated by concerns for humans or any number of other species, researchers, public health advocates, lawyers, elected officials, and community organizers have gone to great efforts and have waged countless battles to limit Pb exposure (Markowitz and Rosner, 2013). Pb has been banned from paint, gasoline, solder, toys, makeup, jewelry, and a host of other products, effectively promoting primary prevention. And yet, the legacy of lead persists in soil. Limiting exposure is a difficult problem, one that requires analysis of systemic interactions on multiple temporal and spatial scales. On the microscale, we focus on soil processes and Pb exposure for individual humans; on the mesoscale, we focus on seasonal cycles of soil resuspension and BLLs; and on the macroscale, we examine group differentiated patterns of exposure and the global extent of this reservoir. In each subsection, we will describe inputs, structures, functions, outputs, and feedbacks of the system.

3.1. Microscale interactions: Lead behavior in soil and impacts on human health

To conceptualize microscale soil lead interactions, we describe the inputs of Pb into soil, the system structure of local soil formation processes and functioning, and the outputs as impacts on human health (**Figure 1**). 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 or milligram per kilogram (Taylor, 1964). Its high density, malleability, and low melting point have enabled it to be 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 (International Lead Association, 2019). Pb extraction has thus facilitated agriculture and urbanization through pipes for water, academic knowledge through the printing press, industrialization and transportation through fuel, paint and batteries, and colonization and genocide through bullets. The first Pb factory in the United States was built in Virginia in 1621, 15 years after colonization began there. Humans have extracted this element from the crustal geosphere and have disseminated and deposited its remineralized forms in soils and strata throughout the globe (Vane et al., 2011; Dean et al., 2014; Waters et al., 2016). Thus, human activities have created a systemic input or stock of Pb into the pedosphere.

When Pb emissions from point sources (i.e., factory sites or peeling paint) and nonpoint sources (i.e., car and airplane emissions) land in soil, the resulting behavior is complex and mediated by various processes including metal speciation, pH, soil organic matter, soil geochemistry, and climate (Sauvé et al., 1998; Kabata-Pendias, 2004; Reeder et al., 2006; Schroth et al., 2008; Mushak, 2011). Pb is largely immobile in soils except under highly acidic conditions, which makes it difficult to remove, unlike elements such as nickel, zinc, or cadmium (Cheng et al., 2011; Ent et al., 2013). Although concentrations of Pb in crustal rocks and naturally occurring soils are generally low and associated with nonbioavailable mineral forms, anthropogenic Pb is often speciated with more bioavailable carbonate, iron, and manganese hydroxide soil fractions (Chlopecka et al., 1996; Kabata-Pendias, 2011). As a result, residual dusts from soils containing

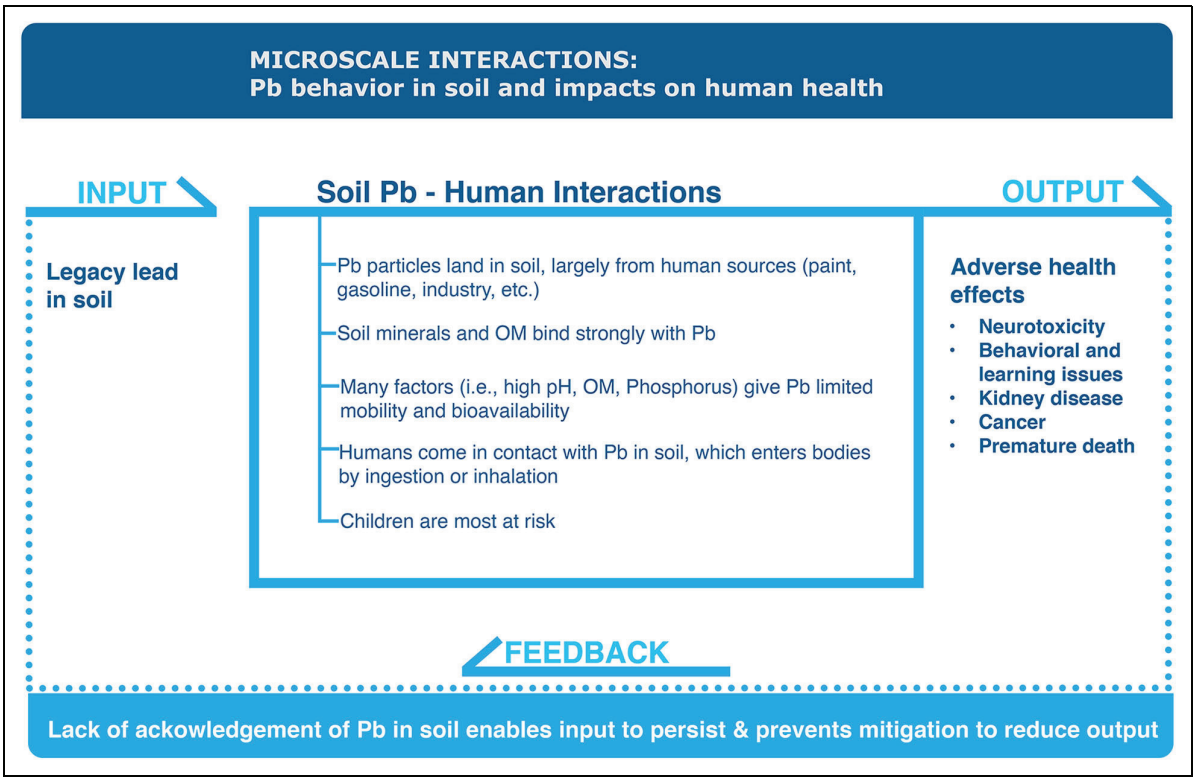

Figure 1. Microscale interactions: Pb behavior in soil and impacts on human health. The system input (upper left) is legacy lead in soil. Once Pb lands in soil, a number of processes occur at a microscale (center box). Soil Pb is largely immobile, but humans, particularly children, are at risk of exposure. The output (upper right) is adverse health effects for exposed humans. There is a positive feedback (bottom) that perpetuates the input, identified here as the lack of acknowledgment of Pb in soil. DOI: https://doi.org/10.1525/elementa.2020.00174.f1

anthropogenic Pb may be more toxic than naturally occurring Pb dust. Lead is associated with the smallest particles in soil, namely the clay and colloidal grain size fractions (Fitzstevens et al., 2017). As such, fine soil particles can be transported as Pb dust which may present higher risks than bulk soils (Laidlaw et al., 2005). The mobility of dust and contaminated fine soil particles is thus a major factor establishing the stock of soil Pb.

When people come in contact with contaminated soils and dusts, the main exposure pathways are incidental ingestion, inhalation, or dermal contact (Spliethoff et al., 2016). Although ingestion has been considered the dominant exposure pathway, associations between air and BLLs suggest that inhalation is also an important pathway, particularly for exposure to microscopic dust particles (Laidlaw et al., 2017). Although exposure to contaminated soils and dusts can occur in a range of outdoor settings, these microscopic particles are frequently tracked into homes (Hunt and Johnson, 2012). The U.S. Environmental Protection Agency (EPA) set the soil screening level (SSL) for children playing in bare soil to 400 mg Pb/kg or ug/g based on exposure and uptake models (U.S. EPA, 1994). Thresholds for indoor surfaces, however, are set as 108 ug/m^2 or 10 ug/ft^2. Converting the outdoor soil standard of 400 ug/g to these units yields a Pb loading of 16,200 ug/m^2 or 1,500 ug/ft^2, which are many times higher than the indoor threshold (Mielke et al., 2007; U.S. EPA, 2020). This means that even soils with concentrations below the EPA SSL contain an extremely high surface reservoir of Pb. These fine soil fractions can become resuspended as dust and present a significant exposure risk, particularly when soils are dry (Clark et al., 2008; Zahran et al., 2013).

After exposure, the degree to which Pb will be absorbed by human systems depends on age (U.S. EPA National Center for Environmental Assessment, 2009). Small children not only ingest more soil relative to body mass but also absorb more Pb through their intestinal tracts (Roberts et al., 2001). The biological processing of inorganic Pb after entry into the human body has been well studied. Inorganic Pb is directly absorbed, distributed, and excreted but is not metabolized. Upon entry to the blood stream, Pb is distributed between blood, soft tissues (such as kidneys, bone marrow, liver, and the brain), and mineralizing tissues (such as bones and teeth). Such mineralizing tissues may contain up to 94% and 75% of the total amount of Pb in adults and children, respectively (ATSDR, 2020). The half-life of Pb in blood is approximately 25 days, 40 days in soft tissue, and more than 25 years in the nonlabile parts of bone. This inert pool of Pb is a particular concern as it may become released into mobile stores over time (Xintaras, 1992).

Once Pb enters the body, it can affect nearly all bodily systems and is particularly noted as a neurotoxin (Needleman et al., 1979; Lanphear et al., 2003). The deleterious

health impacts of Pb are numerous and often irreversible, particularly for children, and include behavioral or learning issues, decreased IQ, hyperactivity, delayed growth, hearing problems, anemia, kidney disease, cancer, and in rare cases can lead to seizures, coma, or death (Bellinger and Bellinger, 2006; Lanphear, 2007; Bellinger, 2011). The Center for Disease Control and Prevention (CDC, 2019) has stated that there is no BLL without harmful effects for children. The CDC lowered the reference value for elevated BLL from 10 ug/dL to 5ug/dL in 2012. This reference value is based on the 97.5th percentile for the U.S. population and is likely to continue declining in the future as BLL declines.

The toxicity of the dose is also dependent on the intensity, frequency, and duration of exposure, and numerous studies show that increases in BLL as a function of soil Pb are not linear. At higher concentrations of soil Pb, BLL increases fall off. The nonlinearity of this dose-response curve is not unique to soil Pb exposures and is also seen with exposure to Pb in air or drinking water (Xintaras, 1992; Laidlaw et al., 2017). Nonetheless, even low levels of exposure can produce an important impact on an individual's lifelong health. The fact that Pb in soil is pervasive but is not considered a primary exposure pathway by many City and State Departments of Health (NYCC, 2018) serves as a positive feedback mechanism, in that efforts to mitigate exposure from soil are not widely undertaken. Leaving soil Pb in place at Earth's surface enables the material to continue to present risks to urban residents, particularly children.

3.2. Mesoscale interactions: Seasonal cycles of soil lead resuspension and BLL fluxes

After tracing interactions at the microscale of soil particles interacting with human bodies, we can broaden the scale of analysis to slightly larger fluxes in time and space. On a mesoscale, we can trace human interactions with soil lead on seasonal time scales and at the spatial scale of a city. A growing body of research examines seasonal cycles of citywide leaded soil and dust resuspension and deposition. Particularly because Pb binds so tightly to soil particles, resuspended soils and dusts carry Pb with them, contributing to wide ranging issues of recontamination (Clark et al., 2008; Laidlaw and Filippelli, 2008; Del Rio-Salas et al., 2012; Laidlaw et al., 2012; Zahran et al., 2013; Engel-Di Mauro, 2020). On the mesoscale of a garden, neighborhood, or city, soils may continually be contaminated by the deposition of suspended dust. Evidence for resuspension has been documented in numerous studies, which show both elevated atmospheric soil and elevated atmospheric Pb in seasonal patterns (Laidlaw and Filippelli, 2008; Laidlaw et al., 2012; Zahran et al., 2013).

Children in urban areas tend to exhibit significant increases in BLLs in summer months (Rothenberg et al., 1996; Mielke and Reagan, 1998; Yiin et al., 2000). In Syracuse, NY, children's BLL increases were observed to be linked with interactions between soil and climate (Johnson and Bretsch, 2002). Research examining the interactions between climate and soil factors affecting Pb dust flux and BLLs was also shown to be significant in Indianapolis, IN, and New Orleans, LA (Laidlaw et al., 2005), Detroit, MI (Zahran et al., 2013), and Milwaukee, WI (Havlena et al., 2009). As aligned with the dry summer peaks in atmospheric Pb, BLL responses also show elevations in summer and declines in winter in a number of studies (Laidlaw et al., 2005; Laidlaw et al., 2012).

This temporal and spatial scale of analysis shows cyclical variation in exposure to and interactions with soil Pb. Children may be exposed to seasonally elevated Pb loading through ingestion or inhalation of suspended soils. This may occur by increased time spent outdoors in summer months or through increased dust entering homes via open windows and doors (Hunt and Johnson, 2012). Particles may penetrate homes from point or diffuse sources, and research conducted in NYC suggests that young people are exposed to particle-associated elements through ambient or outdoor sources, even inside homes (Kinney et al., 2002). Furthermore, dusts and fine fractions of soil have been shown to contain higher concentrations of bioaccessible Pb than bulk soil, which increases the potential risks associated with such exposure (Sharp and Brabander, 2017).

Research conducted in NYC shows that a slightly open window can accumulate Pb dust exceeding the Housing and Urban Development (HUD)/EPA indoor Pb in dust standard of 10 ug/ft^2 (108 μg/m^2) in just 1.5 weeks. (Caravanos et al., 2006). The same group of researchers found indoor dust loadings throughout the five boroughs of NYC exceeding these standards in 86% of samples taken (Caravanos et al., 2006). HUD has shown that soil Pb hazards outside of homes are associated with higher levels of Pb in interior dust. A 2011 report indicates that 20.6% of homes with soil Pb hazards have interior dust hazards, while only 4% of homes without soil hazards also have dust hazards. Results for windowsills are similar—36.8% of homes with soil Pb hazards have windowsill dust hazards compared to only 8.9% of homes without soil lead hazards (U.S. Department of Housing and Urban Development, 2011). As airborne Pb levels have declined due to the phaseout of leaded gasoline, soil resuspension and track-in have been shown to be the primary sources of Pb in house dust in California (Layton and Beamer, 2009). According to Pingitore et al. (2009), soil Pb is the principal source for airborne Pb in urban settings and may set the effective lower limit for future decreases in atmospheric Pb concentrations.

Tracing the seasonal shifts in the exposures to Pb in soil or dust enables us to not only describe systemic interactions at different scales but also enables us to identify an important feedback mechanism. Historical inputs have created elevated stocks of Pb in soil. When soils are bare or dry in summer months, immediate exposure and resuspension into the atmosphere are increased. This resuspension increases the potential for exposure by inhalation and contaminates soils in adjacent regions, increasing the risk of exposure there. Particularly given the association with higher total and bioaccessible Pb on fine particles, resuspension of contaminated soils is thus another positive feedback increasing the systemic input of Pb in soil (**Figure 2**).

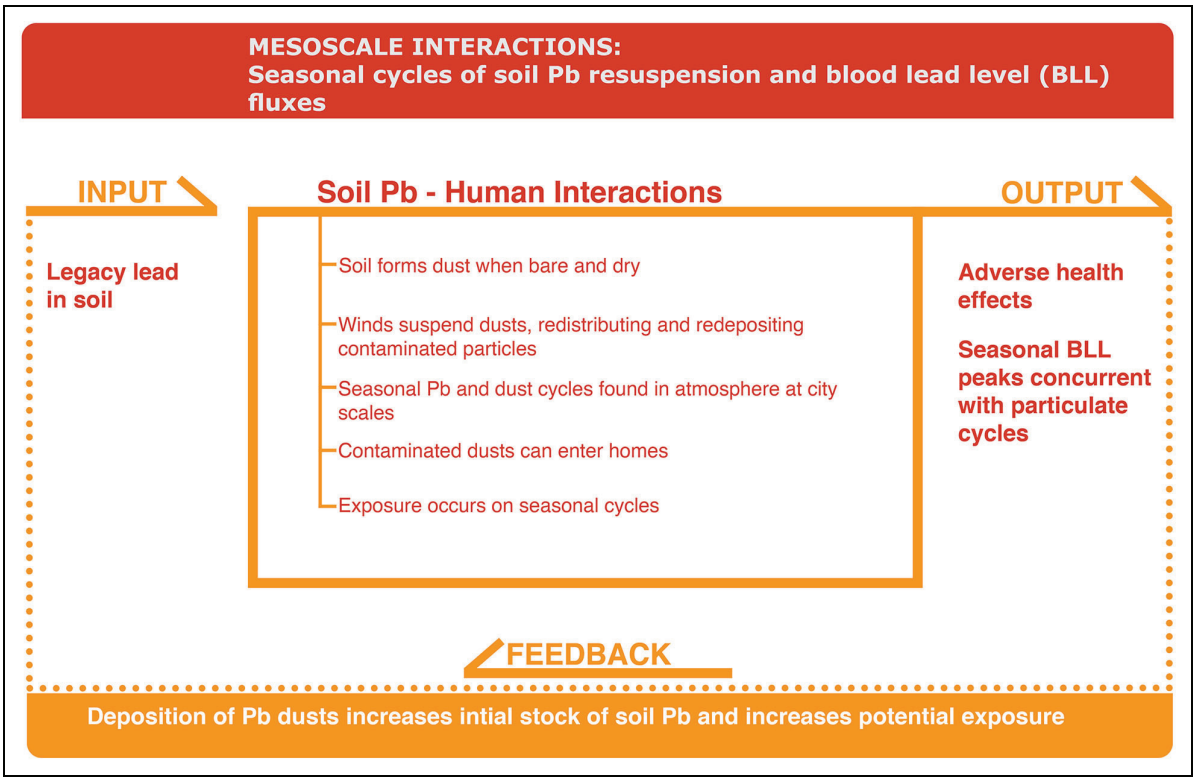

Figure 2. Mesoscale interactions: Seasonal cycles of soil Pb resuspension and blood lead level (BLL) fluxes. The system input (upper left) is legacy lead in soil. Once Pb lands in soil, a number of processes occur at a mesoscale (center box). Contaminated soils can become dry and dusty in summer months, becoming suspended in the atmosphere. Dusts can enter homes and expose people on seasonal cycles. The output (upper right) is adverse health effects for exposed humans, with BLL cycles occurring with seasonal cycles. There is a positive feedback (bottom) that perpetuates the input, identified here as the deposition of Pb dusts. DOI: https://doi.org/10.1525/elementa.2020.00174.f2

3.3. Macroscale interactions: The global extent of soil lead and group differentiated patterns of exposure

Conceptualizing a system of soil Pb interactions on a microscale enables us to see the basic structure and function of Pb behavior in soils and human bodies, the flow of potential exposure pathways, and a positive feedback that enables the input to persist through lack of acknowledgment of risks. Analysis on the mesoscale enables us to see temporal and spatial patterns of exposure, as well as the important positive feedback mechanism of resuspension that may maintain or potentially redistribute risks for exposure. On the macroscale, we can conceptualize larger spatial and temporal patterns of soil Pb deposition that affect the entire globe, as well as the uneven distributions of exposure experienced by differently identified groups of people.

Significant soil Pb contamination has now been characterized in cities throughout the United States and countries throughout the world (Carey et al., 1980; Kovarik, 2005; Yesilonis et al., 2008; Meuser, 2010; Wuana and Okieimen, 2011; Alloway, 2013). In a review of 84 studies of soil Pb in 62 U.S. cities from 1970 to 2012, Datko-Williams et al. (2014) found the well-reported trend that Pb concentrations were higher in urban centers and declined toward suburban and outlying areas. This "bulls-eye" pattern has been documented in numerous cities (Laidlaw and Filippelli, 2008; Filippelli et al., 2015). Although soil Pb has been found to decline over time within certain cities, Datko-Williams et al. (2014) found no statistical correlation between soil Pb and year of sampling, further reinforcing the data suggesting that Pb persists in soil over time. Recent research conducted in New Orleans, however, has shown that soil Pb can decrease over time. Although this is encouraging for the potential to limit exposure, far too many regions of New Orleans and other cities contain elevated soil Pb currently presenting risks (Mielke et al., 2019).

The quantity of Pb residing in the reservoir of soil can be estimated from 5 to 6 million metric tons of Pb used to manufacture both of the dominant sources—paint and gasoline (Mielke and Reagan, 1998). Although lead-based paint was phased out in 1978 as a result of the Lead Paint Poisoning Prevention Act (Farquhar, 1994), deterioration of this paint, particularly by power sanding and scraping, continues to release Pb to soil (Mielke et al., 2001). From the 1920s to 1986, tetramethyl and tetraethyl Pb were added to gasoline. When leaded gasoline was banned in the United States in 1986, 5–6 million metric tons of Pb had been used as an additive, and approximately 75% of this Pb was emitted into the atmosphere (Mielke and Reagan, 1998). Thus, an estimated 4–5

million tons of Pb has been released into the U.S. environment as a result of gasoline emissions (Mielke, 1994). Soil Pb has also been shown to be proportional to highway traffic flow (Mielke et al., 1997).

The transport of Pb to cities and subsequent forms of emissions have generated temporal and spatial patterns that expose residents and workers in proximity. Social formations of class, race, ethnicity, and gender are invoked as we consider the serious environmental injustices that result from the concentration and dissemination of Pb in urban soils. Although exposure to Pb is harmful to all individuals, the disproportionate rates of exposure to soil Pb for people of color and people from low-income backgrounds have been documented in numerous studies (Filippelli and Laidlaw, 2010; Aelion et al., 2013; Leech et al., 2016). McClintock (2015) explores the effects of human and soil Pb interactions for their inextricably linked consequences. Drawing from a Critical Physical Geography perspective, he examines ways in which patterns in soil Pb are related to historical and ongoing processes of capitalist modes of production, and in so doing, critiques the racist ideologies and structures of power that created these patterns. This analysis includes four geospatial maps of Oakland, CA, depicting percentages of the White population, percentages of the population living in poverty, soil Pb in mg/kg, and BLL in ug/dL which show a clear spatial correspondence between soil Pb, BLL, non-White population, and poverty (McClintock, 2015).

These environmentally unjust patterns continue to present what Masri et al. (2020) describe as a "meaningful socioeconomic gradient in vulnerability to exposure to soil Pb" in Santa Ana, CA (Masri et al., 2020). Residential segregation has been well-established as contributing to high rates of Black poverty and inequitable health outcomes (Massey, 2004), and systemic racism has been shown to drive numerous biotic outcomes of urbanized landscapes (Schell et al., 2020). Even while citywide soil Pb levels have been found to be declining in New Orleans, LA, Black residents continue to have higher risks of soil Pb exposure than White residents (Egendorf et al., 2021). Understanding soil Pb-interactions at macroscales of time and space requires reckoning with these racist structures.

Given the ubiquity of Pb in soil, if we continue to expand our macroscale analysis, we may begin to consider the layers of Pb in soil throughout the globe, which may evoke a conceptual marker of the Anthropocene. Although neither Pb nor soil are appropriate stratigraphic markers for the onset of a new geologic epoch (Lewis and Maslin, 2015), there are exceptionally high concentrations of Pb in soils adjacent to human development all over the surface or near-surface layers of this planet (Marx et al., 2016) with detailed chronologies recorded in polar ice (McConnell et al., 2018). Layers of soil Pb therefore provide records of the ongoing ways in which human extraction moves vast quantities of this element from primordial rocks and continues to concentrate and deposit it at Earth's surface, adjacent to vulnerable populations.

Conceptualizing the SES of soil Pb interactions shows microscale mechanisms of exposure, mesoscale cyclical seasonal fluxes in exposure, historically contingent patterns of inequitable distributions in exposed populations by race, and class on macroscales of time and space, and on the largest scale, we see Pb deposits in soil throughout the globe. As tracing the micro- and mesoscale cycles enables articulation of positive feedbacks, so does this macroscale interaction. People with more structural power have been less affected by soil Pb and therefore have less impetus to make changes that could shift burdens of exposure. People from low-income backgrounds and people of color have been more impacted by this issue and have historically had less access to structural power. Less access to structural power limits such communities' abilities to change patterns of exposure, either through changing individual circumstances (i.e., moving to less-contaminated areas) or through leveraging structural resources (i.e., shifts in policy or remedial actions). As such, unequal access to resources enables the cycle of uneven exposure to continue as a positive feedback perpetuating the initial inputs of legacy lead in the system (**Figure 3**).

4. Identifying interventions for mitigating soil lead exposure

Having outlined the component elements, structure, functions, and feedbacks of the soil Pb system at a variety of scales, we have a clear picture of the interconnected and dynamic shapes of this system over time and space. The goal of articulating this system is to be able to understand and, ultimately, experiment with the opportunities and limits for interacting with and changing it to support desired systemic outcomes. Before we embark on discussion of such experiments, we must explore what has been attempted before. What interventions for mitigating soil Pb exposure have been attempted at various scales? What works, what doesn't, and why?

Primary prevention of environmental Pb exposure has occurred through efforts such as limiting Pb in solder, paint, and gasoline. Although these have been tremendous successes, the presence of Pb in soil persists, and standard medical interventions for mitigating Pb exposure continue to focus on education and household dust cleanup. The Cochrane Collaboration conducts evaluations of various medical interventions, and numerous Cochrane reports have evaluated such education and household interventions for preventing Pb exposure. The most recent report clearly states the following:

> *Based on current knowledge, household educational interventions are ineffective in reducing blood lead levels in children as a population health measure. Dust control interventions may lead to little or no difference in blood lead levels . . . . There is currently insufficient evidence to draw conclusions about the effectiveness of soil abatement or combination interventions . . . . Further trials are required to establish the most effective intervention for preventing lead exposure. Key elements of these trials should include strategies to reduce multiple sources of lead exposure simultaneously using empirical dust clearance levels. (Nussbaumer-Streit et al., 2016)*

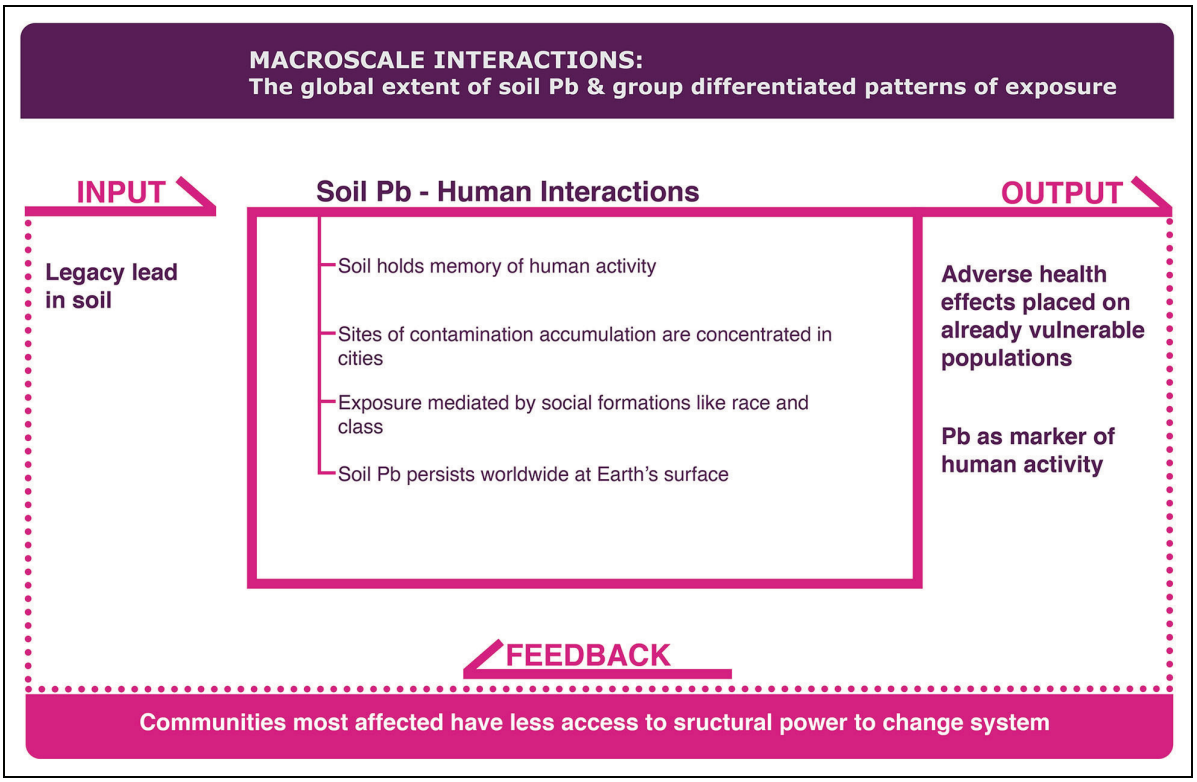

Figure 3. Macroscale interactions: The global extent of soil Pb and group differentiated patterns of exposure. The system input (upper left) is legacy lead in soil. Once Pb lands in soil, a number of processes occur on the macroscale (center box). Soil Pb has accumulated around the world but has been concentrated in cities, disproportionately exposing people of color and people from low-income backgrounds. The output (upper right) is adverse health effects on already vulnerable populations and markers of human activity around the world. There is a positive feedback (bottom) that perpetuates the input, identified here as affected communities lacking access to structural power needed to change the system. DOI: https://doi.org/10.1525/elementa.2020.00174.f3

The fact that the standard interventions (focused on household dust and education) are deemed ineffective for reducing Pb exposure is another positive feedback mechanism that perpetuates further lead exposure, an issue with enormous medical and societal consequences (Bellinger, 2011). What is additionally problematic is that these standard interventions are only being made after children show elevated BLLs, thus using children for identifying the presence of environmental contaminants. Such an approach violates national and international standards for treatment of human subjects. As Mielke (2015) writes,

> *According to World Medical Association (2013) criteria, if a method is shown to be ineffective, then the medical community must revise the intervention to prevent harm. The U.S. treatment protocols are thus doubly culpable because not only do they employ children's blood lead as an indicator of lead contamination, but they also use an ineffective intervention method to prevent children from further harm.*

Although the Cochrane Collaboration states that there is "insufficient evidence to draw conclusions about the effectiveness of soil abatement or combination interventions," here we discuss what is available in the literature with regard to various scales of soil Pb exposure interventions.

4.1. Microscale interventions: Changing soil lead bioavailability

On the microscale, we focus attention on interventions that are made within soils, specifically focused on changing the bioavailability or speciation of Pb. As mentioned previously, the degree to which a contaminant will negatively impact human health is not only determined by a person's age, health, and duration and frequency of exposure but also by the bioavailability of the contaminant or the fraction of the chemical dose that may be absorbed in human systems. Quantifying the degree to which Pb will pass through the human intestinal lining is problematic to assess in living organisms (in vivo), so in vitro lab assays such as physiologically based extraction tests were designed to simulate biological systems of interest. The term "bioaccessibility" is therefore used to describe the outcomes of such in vitro tests and to approximate bioavailability, depending on relevant in vivo models (Ruby, 2004). There are numerous methods to determine these values, and the accuracy of various assays have been in question by researchers for some time (Henry et al., 2015).

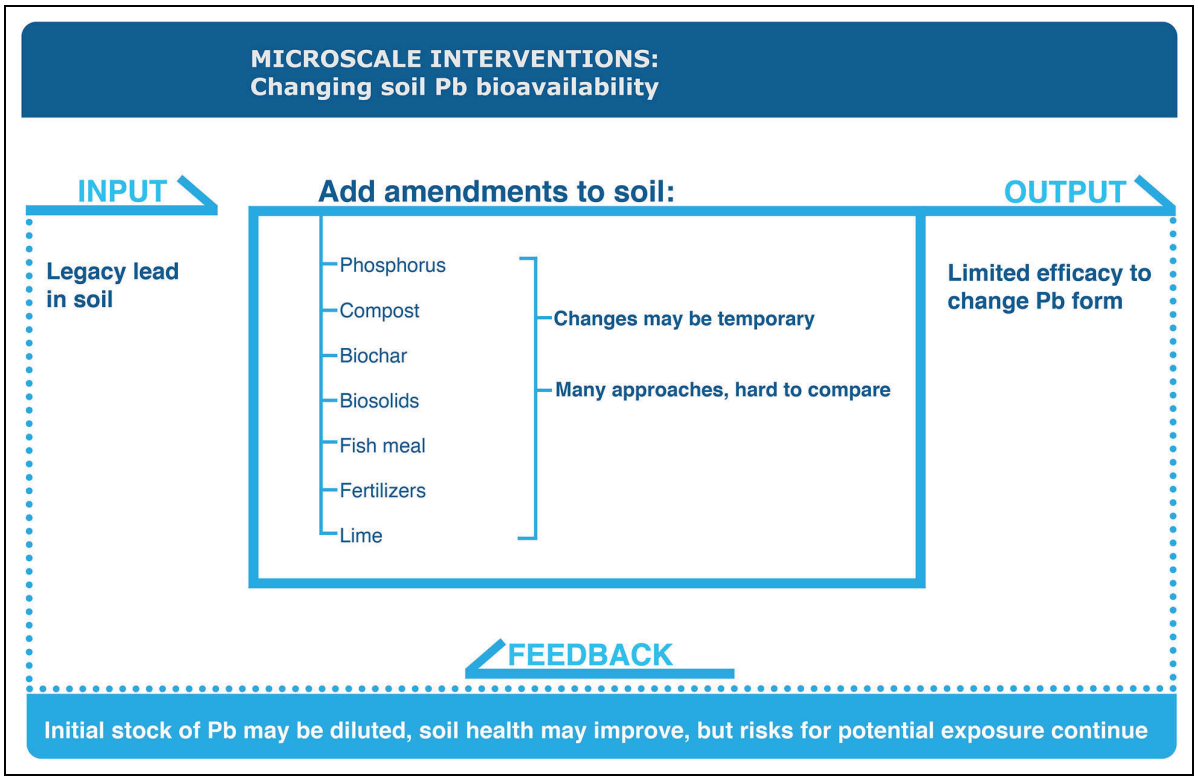

Figure 4. Microscale interventions: Changing soil Pb bioavailability. The system input (upper left) is legacy lead in soil. To address this issue, people have attempted a number of interventions on the microscale (center box). Amendments such as phosphorus, compost, biochar, and others have been added to change soil Pb bioavailability, but these changes may be temporary and are hard to compare across approaches and lab assays. The output (upper right) is limited efficacy to change Pb form. Although amendments may dilute the overall Pb concentrations and improve soil health, there is a positive feedback (bottom) that perpetuates the input, identified here as legacy Pb remaining in surface soils. DOI: https://doi.org/10.1525/elementa.2020.00174.f4

One of the primary methods to potentially change the form of Pb in soil and subsequently change its bioavailability is to add amendments (Hettiarachchi and Pierzynski, 2004). Organic amendments, such as compost, manure, biosolids, and municipal solid wastes, are frequently added to soils as sources of nutrients and to enhance physical properties and fertility. Amendments that are low in metal(loid)s may reduce the bioavailability of soil Pb by adsorption, complexation, or reduction (Bolan et al., 2014). Pb-phosphate minerals in the form of pyromorphite have been shown to be highly insoluble and less bioavailable than other mineral forms. As such, numerous methods for adding phosphorus to soil to assist in formation of such minerals have been investigated. A number of studies suggest that biosolids are effective in rendering soil Pb less bioaccessible, particularly as a result of Pb absorption on Fe oxides (Brown et al., 2003; Brown et al., 2012). Composted biosolids and composted food and yard-waste may also be effective for such purposes (Attanayake et al., 2014; Defoe et al., 2014; Attanayake et al., 2015). Biochar has also been shown to reduce Pb bioaccessibility (Park et al., 2011; Méndez et al., 2012).

Determining the degree to which amendments change Pb bioaccessibility depends on the methods used (Obrycki et al., 2016). Many such changes are dependent on soil pH, which can also change over time (Scheckel et al., 2013). As organic matter decomposes, the changes to the form of Pb in soil may also be reversed. Adding amendments in the form of phosphorus or compost is generally a good way to promote soil biological and physical health, and dilute contaminant concentrations, but other issues resulting from runoff or increased nutrient loading to aquatic systems can contribute to environmental issues such as eutrophication (Conley et al., 2009; Paltseva et al., 2018b). Phosphorus additions may also increase arsenic (As) availability. Using amendments requires careful attention to detailed procedures that may not be easy for gardeners to carry out (Paltseva et al., 2018a, 2018b). Thus, while adding amendments may potentially change overall Pb bioavailability, it will not completely mitigate potential risks for exposure (**Figure 4**).

4.2. Mesoscale interventions: Phytoextraction to remove lead and phytostabilization to sequester lead

Examining interventions on a mesoscale can take us beyond the elemental and molecular changes of Pb in soil and consider interventions that include the broader soil system, larger plots of land, and a particular focus on plants growing in situ. The use of plants to remediate soil

has been investigated in numerous lab settings, on agricultural fields, and on former mining sites and is part of an emerging field of phytotechnology. Phytotechnologies in general, and phytoremediation in particular, refers to a range of plant mechanisms for breaking down, sequestering, uptaking, or volatilizing contaminants in soil, sediment, and water. Numerous plant species have been shown to be effective for breaking down organic contaminants (Kabata-Pendias, 2004), and a number have also been shown to effectively uptake metals like arsenic, cadmium, and zinc (Ali et al., 2013).

The use of plants to remediate Pb, however, is a contested issue, rife with misconceptions (Blaustein, 2017; Egendorf et al., 2020). Because Pb is highly immobile in soils (Sposito, 2008), and because plants have many mechanisms to limit Pb uptake through roots (Kumar and Prasad, 2018), most plants exhibit limited Pb uptake, if any at all. However, particularly through the use of chelating agents that make Pb more mobile in soils, some studies suggest that plants such as sunflowers (*Helianthus anuus*) and mustards (*Brassica juncea*) have the potential to phytoextract (and essentially remove) Pb from soil (Tangahu et al., 2011; Paliwal et al., 2015). The use of chelating agents in these cases, however, has been shown to present greater risks of mobilizing Pb to groundwater and is therefore not viable from a remedial perspective (Chaney et al., 2002). Numerous researchers agree that plants capable of phytoextraction must be able to uptake high quantities of the element of concern without the use of chelating agents (van der Ent et al., 2013).

Without the use of chelating agents or artificial conditions, some very select species may be able to uptake some Pb through their roots. However, the time it would take to uptake enough Pb to sufficiently remediate any soils with high concentrations would be significant (Butcher, 2009). Estimates suggest that time frames for remediation of soils with high Pb contamination may take 200 years (Arshad et al., 2008). Additionally, when above ground shoots and leaves of various plants have shown elevated Pb concentrations, the degree to which plant-Pb concentrations are a result of surface contamination versus uptake through roots is unclear, which calls into question such plants' phytoextraction potential (van der Ent et al., 2013). No hyperaccumulator, that is, a plant that can meet a number of criteria (including concentrations of 1,000 mg Pb/kg in dry weight aboveground tissue, greater ratios of shoot Pb to root Pb, and greater ratios of shoot Pb to soil Pb), has been found (Egendorf et al., 2020). As such, phytoextraction is not a viable option for effectively reducing soil Pb exposure.

On the other hand, phytostabilization, where plants are used to maintain contaminants in place, is an effective way to cover contaminated soil, as long as the plant communities are maintained (Butcher, 2009). When considering the mesoscale interactions of resuspended dusts around a city, planting a wide range of perennial species (particularly inedible ones to limit risks of Pb entering the food chain), can be a highly effective intervention to limit dust. Numerous researchers have investigated the potential of Pb phytostabilization and have demonstrated that this approach can promote human and greater environmental protection in a variety of settings (Dickinson, 2000; Robinson et al., 2006; Meeinkuirt et al., 2012; Radziemska, 2018; **Figure 5**).

4.3. Macroscale interventions: Emplacing clean soil

For primary prevention of Pb poisoning, all potential sources of environmental Pb exposure must be isolated or remediated before children enter the environment (Laidlaw et al., 2012). The U.S. Federal Government has created legislation protecting clean air (U.S. EPA Office of Air and Radiation, 1970) and clean water (USEPA Federal Water Pollution Control Amendments of 1972), but there is no universal clean soil act. Without such measures in place, which interventions address soil Pb on the large scale?

Given that remediation or extraction of Pb from soil is unfeasible on human time scales, the most effective way to reduce soil Pb exposure is to remove the contaminated soil. Excavation and replacement can happen on a very short time scale but requires tremendous cost, labor, and logistical coordination. Removing contaminated soil also places the burden elsewhere, most commonly into landfills. Excavation and soil disturbance can also present risks for dust and contaminant redeposition. However, numerous studies have investigated the efficacy of covering contaminated soil in situ, with promising results. Such research demonstrates a significant reduction in soil contamination when new soil is brought in to replace the previously contaminated material (Laidlaw et al., 2017). The costs of simply covering contaminated soil with a permeable geotextile like landscape fabric are far lower than excavating and frequently lower than amending soil. As long as the cover is maintained, this method is effective for mitigating exposure (Mielke, 2016). Covering or replacing contaminated soil has also been shown to reduce levels of exterior Pb dust, as well as reduce Pb dust loading inside home entryways, floors, and windowsills (Clark et al., 2004). Yard covering interventions with a range of nonsoil materials have also been shown to be effective for such purposes (Binns et al., 2004; Dixon et al., 2006). This intervention is therefore a negative feedback in the human–soil Pb system, essentially reducing the initial input of legacy lead in soils (**Figure 6**).

Not only does emplacing new soil reduce surface Pb contamination, but it can also have an effect on reducing children's BLLs. Numerous studies have documented significant reductions in BLLs when clean soil replaces contaminated material (Laidlaw et al., 2017). In one example, Lanphear et al. (2003) demonstrated that soil abatement was associated with a statistically significant decline in children's BLLs as well as a reduction in concentrations of indoor Pb dust, particularly when compared with homes where external soils were not replaced. Both empirical dose response studies and EPA integrated exposure uptake biokinetic models demonstrate that children's BLLs can be maintained below 5 ug/dL if soil Pb concentrations are maintained at 40 mgPb/kg (Zahran et al., 2011; Mielke et al., 2016). The question then becomes: Where can new soil be obtained? A few centimeters of

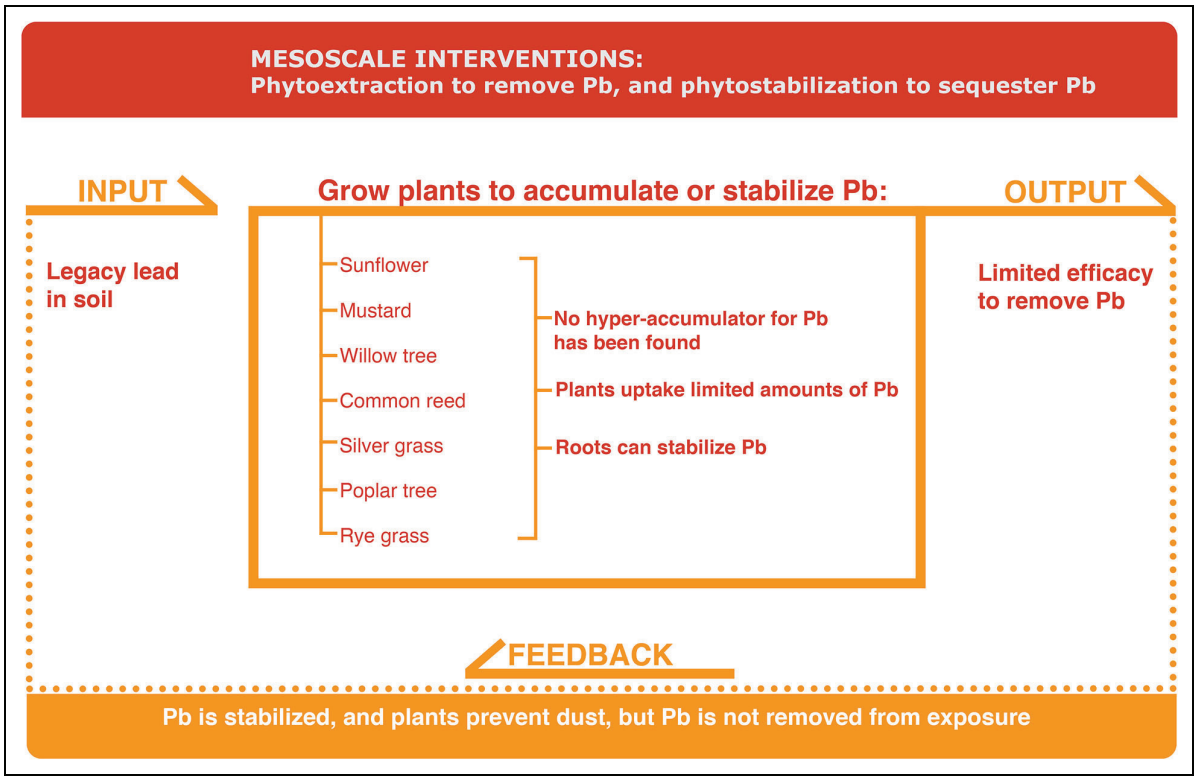

Figure 5. Mesoscale interventions: Phytoextraction to remove Pb and phytostabilization to sequester Pb. The system input (upper left) is legacy lead in soil. To address this issue, people have attempted a number of interventions on the mesoscale (center box). Many different plants have been grown to potentially accumulate and extract Pb (phytoextraction). However, no confirmed hyperaccumulator has been found to efficiently remove Pb from soil. On the other hand, many plant roots can effectively stabilize Pb in soil (phytostabilization). The output (upper right) is limited efficacy to remove Pb from soil. Although plants may stabilize Pb and prevent dusts, there is a positive feedback (bottom) that perpetuates the input, identified here as legacy Pb remaining in surface soils, not being removed from potential exposure. DOI: https://doi.org/10.1525/elementa.2020.00174.f5

topsoil can take hundreds of years to form naturally and removing soil from exurban settings depletes the ecosystem from which it is taken. Constructing soil from inorganic and organic materials is a promising way to address the urgent need for clean urban soil, as will be discussed in the following sections (Sere et al., 2008; Sloan et al., 2012; Rokia et al., 2014; Deeb et al., 2016; Egendorf et al., 2018; Deeb et al., 2020).

5. Conducting applied and participatory experiments for mitigating soil Pb exposure in NYC

Capping and covering sites with clean soil may well be the most feasible and cost-effective approach to mitigating Pb soil exposure risks. Since the limiting factor for this approach is availability of clean soil, pilot studies in NYC are examining the potential for constructed soils to meet this need. The NYC Clean Soil Bank and PURE Soil NYC programs were initiated by the NYC Mayor's Office of Environmental Remediation (OER), using thoroughly tested glacial sediments excavated from development sites for various forms of beneficial reuse (Walsh et al., 2018). In 2014, OER began collaborating with researchers from the City University of New York Brooklyn College to study the extent to which these sediments could serve as viable growing media (Egendorf et al., 2018). This pilot study investigated sediments mixed with various ratios of compost and demonstrated that the constructed Technosols were safe and effective for growing produce and limiting Pb exposure. The most important obstacle for establishing this study was obtaining compost with low Pb concentrations. Ensuring compost is thoroughly tested and is produced in ways that prevent Pb incorporation could potentially be a limiting factor in future work and is a topic of concern in the broader field of constructed Technosols, which investigates the use and development of newly created soils. This field is emerging within global soil science and is becoming more urgent in the midst of worldwide soil depletion, degradation, and contaminant concerns (Séré et al., 2008; Macía et al., 2014; Morel et al., 2015; Jordán et al., 2017; Deeb et al., 2020).

Follow-up studies for this applied research are being conducted and are currently emphasizing participatory methods at various scales (**Figure 7c**). Each intervention is being created in collaboration with multiple stakeholders and is focused on collecting data that is meaningful to affected communities. Results will be strategically disseminated, and together, academics and researchers

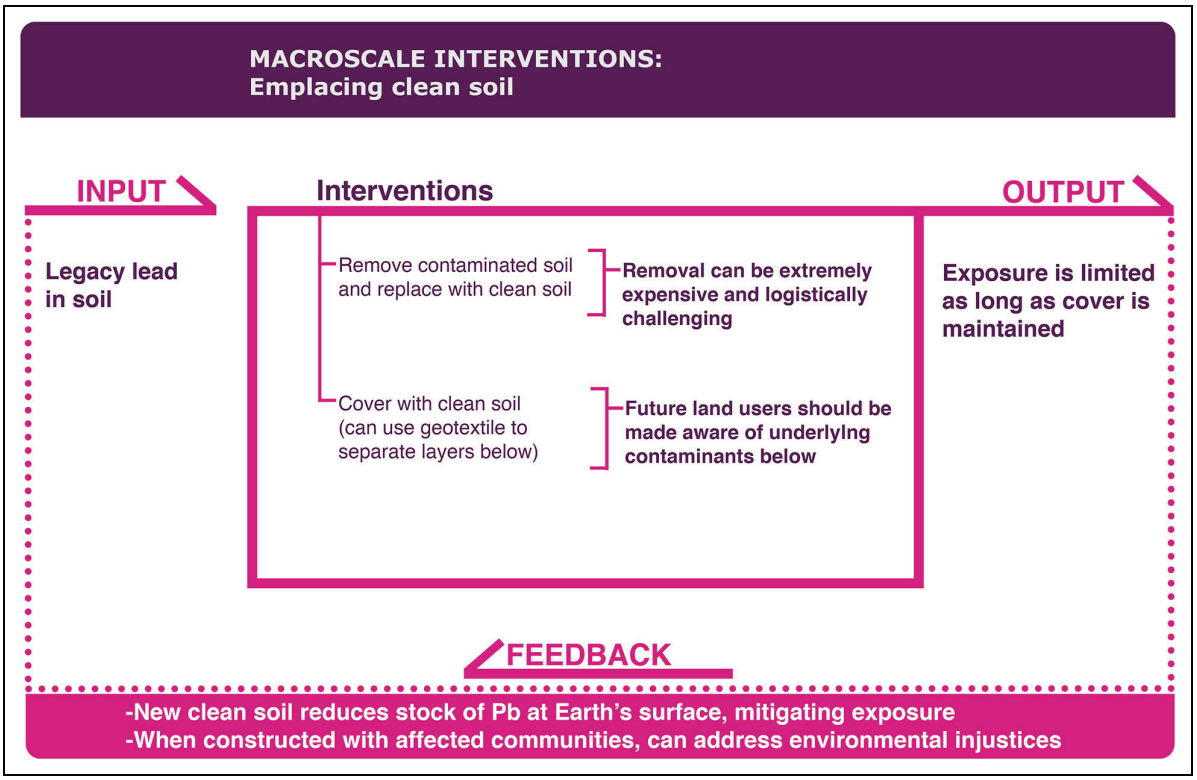

Figure 6. Macroscale interventions: Emplacing clean soil. The system input (upper left) is legacy lead in soil. To address this issue, people have attempted a number of interventions on the macroscale (center box). Contaminated soil can be removed and replaced with clean soil. Although this is an effective way to limit exposure, removal can be extremely expensive and logistically challenging. Covering contaminated soil and separating new layers with barriers like geotextiles can also mitigate exposure. However, future land users must be made aware of underlying contaminated layers. The output (upper right) is limited exposure to Pb in soil, as long as a cover is maintained. Unlike the other investigated interventions (see **Figures 4** and **5**), emplacing clean soil creates a negative feedback on the system (bottom), reducing the initial input. Clean soil layers reduce the stock of Pb at Earth's surface, mitigating exposure. When soils are constructed with affected communities, this intervention can also address environmental injustices. DOI: https://doi.org/10.1525/elementa.2020.00174.f6

with expertise outside of academia will be evaluating the degree to which interventions achieve goals at each scale. Such evaluations will then enable revision to the experiments as necessary, in order to more effectively engage in ongoing systems research and change. The overarching question and aims driving these efforts are as follows:

– How can the Clean Soil Bank effectively limit exposure to legacy lead in soil?

- Microscale: Conduct participatory research on new soil mixtures with affected communities to create research relevant to users (Carbon Sponge and JUST SOIL).
- Mesoscale: Evaluate soil and infrastructure development over time to enable strategic creation of clean soil distribution systems (Legacy Lead, East New York Healthy Soils Initiative).
- Macroscale: Quantify contaminant cover and support policy, infrastructure, and funding for soil distribution in NYC and beyond (Clean Soil Bank Stockpile, widespread Anthrosol construction).

Each of these collaborative research endeavors will be briefly discussed in the sections below. Formalized research objectives, hypotheses, methods, results, and discussions will be made available in forthcoming articles.

5.1. Microscale applied and participatory experiments: Carbon Sponge and JUST SOIL

Before the Clean Soil Bank sediment and compost mixtures can be used on a large scale, more information is needed in order to understand how these new soils form and function with a range of parent materials, in a variety of settings, and for different plant types and community uses. The first pilot study begun in 2014 (Egendorf et al., 2018) evaluated one type of compost and one type of sediment used in three community gardens in Brooklyn,

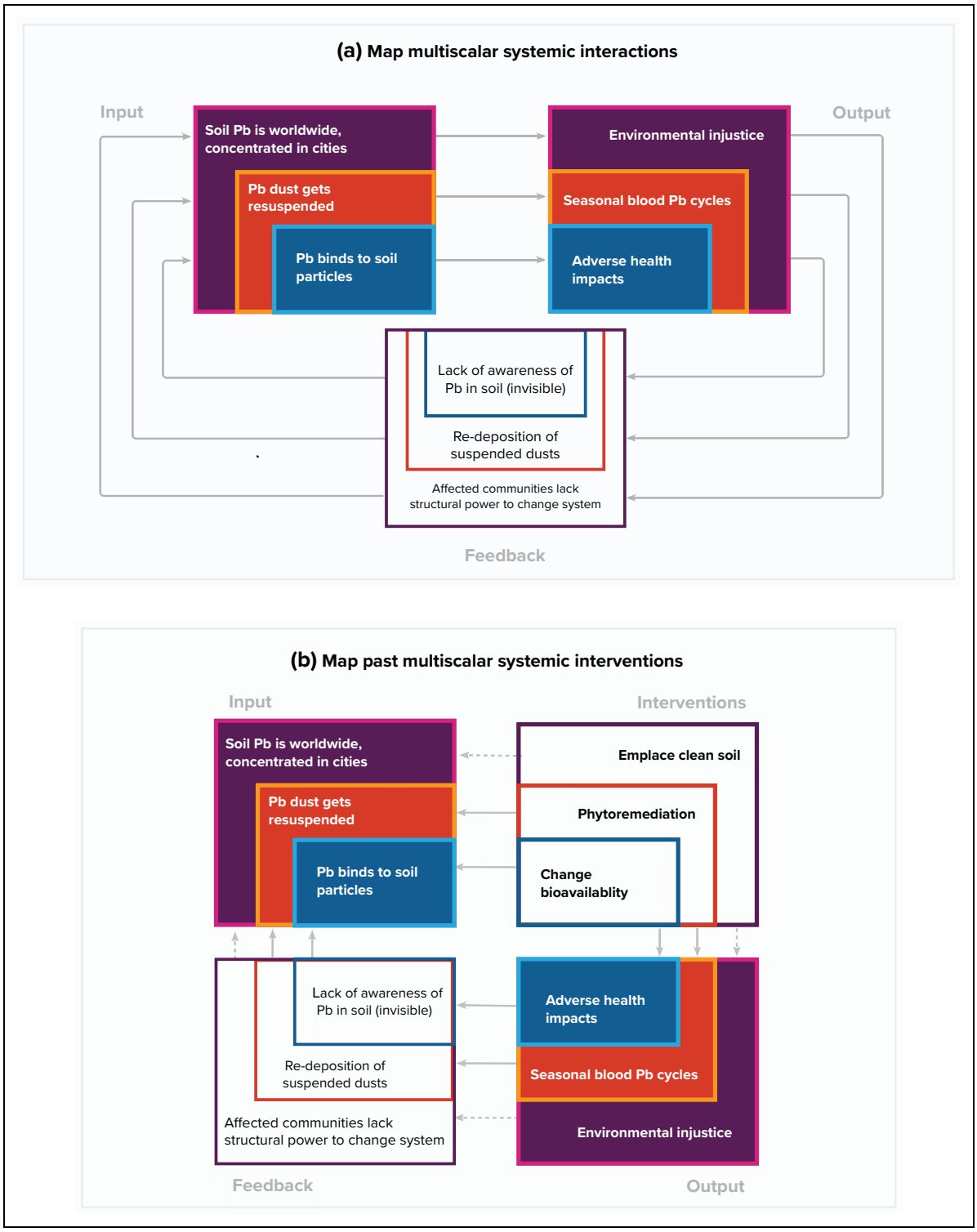

Figure 7. Systems framework overview. The goal of this framework is to offer a structure for understanding and experimenting with complex social-ecological systems (SES) toward just and sustainable outcomes. There are three steps, illustrated here with the example of addressing legacy lead (Pb) in soils, situated in New York City, NY, USA. DOI: https://doi.org/10.1525/elementa.2020.00174.f7

Figure 7a shows the first step of the framework: to map the system at multiple scales. This involves identifying the system's inputs, outputs, feedbacks, and the degree to which the feedbacks increase or decrease the initial inputs (positive or negative feedbacks). Understanding the processes that occur to link the inputs to the outputs is also essential to identify for each scale (see **Figures 1–3** for more details and descriptions of processes). In this summary figure, we see the initial inputs of Pb in soil and a summary of the behavior at each scale: Pb binding to soil particles

NY. Two participatory follow-up studies are currently underway. One study uses a sandy glacial sediment type mixed with 33% compost produced by the NYC Department of Sanitation (DSNY) and eight different plant covers: bare soil, sunflowers, edible crops, cover crops, sunflowers and edible crops, sunflowers and cover crops, edible crops and cover crops, and sunflowers, edible crops, and cover crops. Three replicates of each bed type were made to create 24 beds in total. The purpose of this study is to evaluate the impact of plant type and plant interactions on constructed Technosol biology, chemistry, and physics, with particular attention to nitrogen cycling and carbon sequestration potential (www.carbonsponge.org). This study is being conducted with artists, horticulturalists, educators, and scientists and exists as an interactive exhibit at the NY Hall of Science in Queens, NY (https://nysci.org/home/programs/designers-in-residence/).

The second follow-up study uses another sandy glacial sediment type mixed with six ratios of compost produced by the NYC Compost Project Hosted by Big Reuse: 0, 10, 20, 30, 40, and 50%. Three replicates of each compost ratio bed were created to produce a total of 18 beds. Each mixture was planted with the same number and variety of edible crops: collards, peppers, tomatoes, basil, and onions. The purpose of this study is to evaluate the same soil biological, chemical, and physical parameters of these constructed Technosols as are being evaluated in the Carbon Sponge plots, but this study focuses on the impacts of compost quantity instead of plant community on soil formation and function. Perhaps the most important aspect of this project is that it is being co-created with young

(microscale), soil Pb becoming suspended as dusts (mesoscale), and worldwide dissemination of Pb in soils concentrated in cities (macroscale). These inputs and processes produce the outcomes of adverse health impacts, seasonal cycles of adverse health impacts seen by blood Pb level (BLL) fluctuations, as well as environmental injustices—disproportionate impacts borne by low-income populations and communities of color. There are a number of positive feedbacks that perpetuate this system, here identified as a lack of awareness, the redeposition of suspended dusts, and the fact that the most impacted communities lack access to the structural power necessary to change the system.

Figure 7b shows the second step of the framework: to identify past/ongoing interventions (attempts that individuals or groups have made to change the system). Invariably, if an SES is not functioning toward just and sustainable outcomes, such attempts have been made, and it is important to identify what effectively changes the system, what does not, and why. Here, we identify interventions at three scales: changing bioavailability (microscale), phytoremediation (mesoscale), and emplacing clean soil (macroscale; see **Figures 4**–**6** for more detailed explanations of each). Changing the bioavailability of Pb may make its form less harmful to humans, but methods to do so vary and effectiveness is not guaranteed. As such, this intervention perpetuates the output of adverse health effects and soil Pb continuing to expose populations (positive feedback). Phytoextraction or removing Pb with plants is not safe or effective on human time scales, so this too perpetuates the presence of Pb in soil and resuspension and deposition of dusts (positive feedback). Phytostabilization, the process by which plants stabilize or sequester Pb in situ, may prevent dusts as long as plant cover is maintained (and is a potential negative feedback, not depicted here [but is represented in **Figure 5**]). Emplacing clean soil, however, can effectively reduce exposure to legacy Pb in soil as long as the new soil cover is maintained (not dug up or removed). This can thus reduce exposure on a microscale, reduce suspension of Pb dusts on the mesoscale, and reduce environmental injustice on a macroscale, particularly when affected communities are involved in the process. As such, we identify the process of emplacing clean soil as a negative feedback on the input or stock of legacy Pb in soil.

Figure 7c shows the third step of the framwork: once the system and attempted interventions are understood (Steps 1 and 2), Step 3 involves experimenting with interventions that can produce just and sustainable outputs. Because emplacing clean soil was the only intervention we identified that is capable of reducing the harmful input of legacy Pb in soils (the only negative feedback), this becomes the new experimental input we work with at a variety of scales. On the microscale, we have begun co-constructing and emplacing new soils with impacted communities, and the JUST SOIL project is one such example where we work with youth and NYC Housing Authority residents on this applied research. On the mesoscale, we have been piloting clean soil distribution with East NY Farms, to make clean soil available to residents and community gardeners throughout an impacted neighborhood in Brooklyn, NY. On the macroscale, the NYC Mayor's Office of Environmental Remediation (OER) has created a Clean Soil Bank stockpile, a site with 12,000 cubic yard capacity for the first municipal clean soil reuse and distribution system in the United States. This program provides the inorganic substrate for the meso- and microscale projects and is enabling policy and infrastructure for clean soil distribution on the macroscale. Each of these experiments is poised to produce healthy, sustainable, and just outputs since they not only reduce the surface stock of legacy Pb in soil but also promote waste reduction, additional urban green space, and ecosystem services and are being created in collaboration with impacted communities with the goals of food justice and food sovereignty. Although each of these experiments is relatively new and ongoing, we expect them to create positive feedbacks of more awareness of Pb in soil, reduced Pb in the atmosphere, and enhanced structural power for impacted communities, which will perpetuate and increase the just and sustainable inputs. We believe that this framework can help address issues of Pb in soil in other locations and we hope it will be effectively applied to experiment with changing other SES toward just and sustainable outcomes.

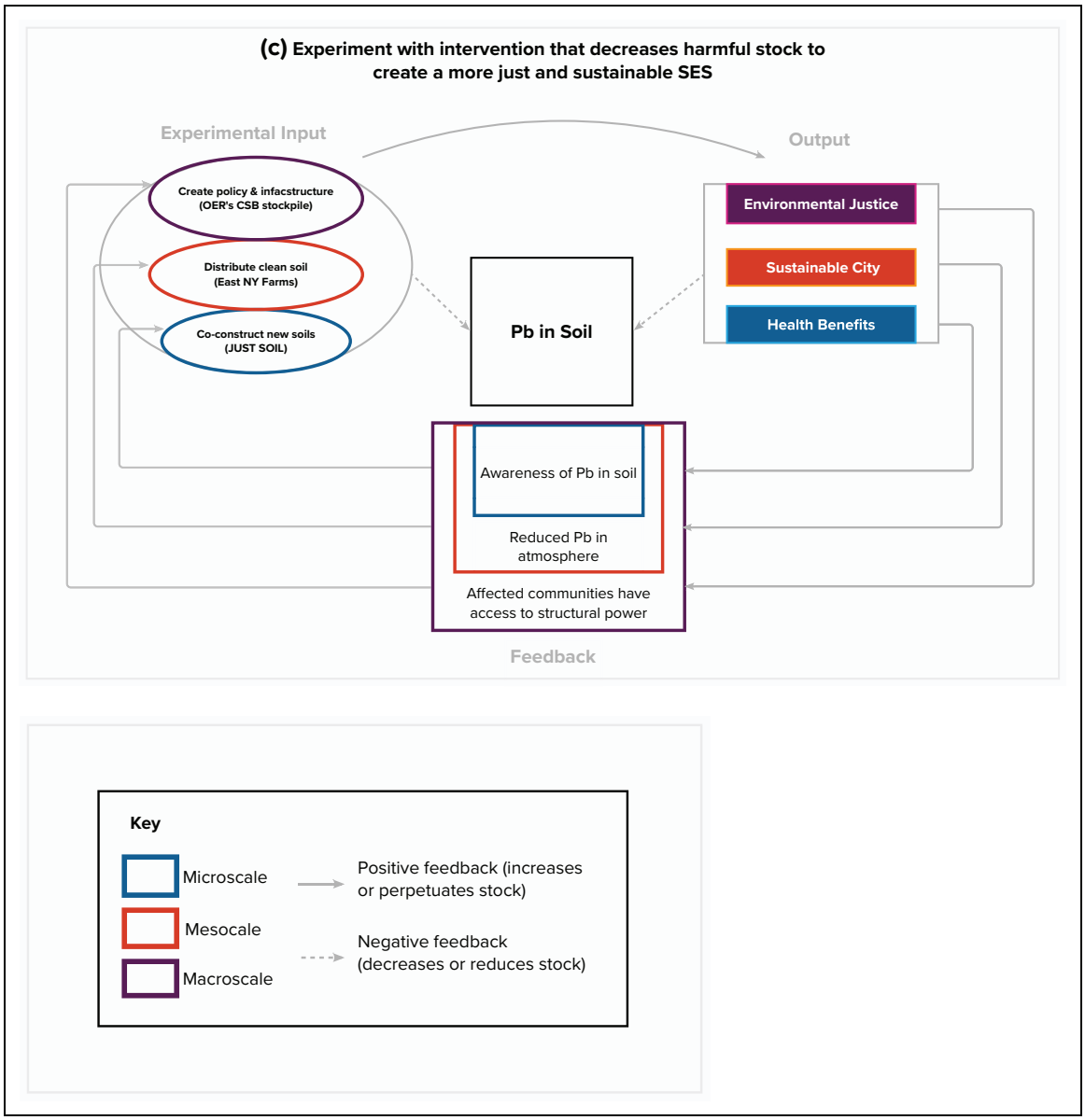

Figure 7. (*Continued*)

people and gardeners from a NYC Housing Authority community. This JUST SOIL team emphasizes engaging affected communities on the EJ aspects of this work (https://twitter.com/justsoilnyc). Youth and gardeners are collaborating in each stage of the research: The group of individuals with expertise outside of academia helped frame research questions, are co-conducting both field and laboratory analyses, and will evaluate results and present data as they become available. This project seeks to be in alignment with CPAR (see Stoecker, 1999; McKenzie, 2009; Torre et al., 2012; Fine, 2018).

5.2. Mesoscale applied and participatory experiments: Legacy lead and clean soil distribution

In January, 2016, 20+ organizations began convening in NYC as the Legacy Lead Coalition to collaboratively address soil Pb contamination and create a clean soil distribution network. Legacy Lead is a coalition of concerned residents, city employees, scientists, advocates, and greening organizations collaborating to assist fellow New Yorkers in reducing potential harm from Pb in soil. Participants have gathered regularly to share informational and material resources for systematically mitigating soil Pb exposure. One of the primary strengths of this group is in being a coalition and not a formal organization or entity. The flexible structure not only allows the group to easily evolve but also enables members of various institutions and agencies to come to meetings without potentially conflicting with employer time or interests. The group exists as a network where individuals can share information and resources from their organizations and bring such information and resources back.

Research questions being addressed by this network include: How can a coalition build and support soil Pb

education? How can such a diverse and diffuse entity further soil research? And perhaps most importantly, how can a coalition experiment with the creation of a clean soil distribution network? In response to each of these overarching questions, the coalition has created accessible educational materials (an illustrated story of the bio-geo-socio-chemical Pb cycle), revamped best management practices (BMP) signage and handouts, and is connecting with numerous garden education networks. Although household educational interventions have not been shown to be effective for preventing Pb exposure, the educational endeavors of the Legacy Lead coalition pertain directly to engaged gardening, horticultural, and agricultural communities with a vested interest in understanding their soils. Although behavior changes such as washing produce and leaving dust outside of homes are encouraged, the focus of the coalition has been on constructing new soil and creating possibilities for primary prevention. Members of the coalition are also the individuals and groups who made it possible to connect with the follow-up pilot studies mentioned in the previous section. Without the continued collaboration and regular contact between organizations, it would not have been possible to connect the sites with the material and informational resources required for these studies.

One goal of Legacy Lead is to support vulnerable populations in not only receiving clean soil but also in creating and disseminating such valuable material (soil) and associated informational (background info, BMPs) resources. Residents of public housing are ideal candidates for such collaboration, but it was important that collaboration occur as a request from such a community, and not as an initiative from scientists, in order to attend to power structures within the research process and uphold the tenets of PAR. Relationships built within the Legacy Lead network enabled this request and connection to be made and sustained over time.

The need for clean soil to mitigate Pb exposure and promote urban green space is clear. The microscale experiments of constructing and understanding new soil for this purpose can enable the mesoscale experiments on creating a distribution network, just as the mesoscale network of Legacy Lead fostered the connections that enabled the microscale field experiments. In the vein of use-inspired basic research, these opportunities can be conceptualized as applied systemic experiments. Understanding the current systems of material resources such as excavated sediments and municipal compost is enabling opportunities for experimentation with the materials and between city agencies and organizations. Members from the 20+ organizations within Legacy Lead are essentially components of the human system that are experimenting toward creating a system for soil construction and distribution. Observing and analyzing results of moving materials around the city will continue to enable the system to be revised and adjusted before it is emplaced in a more fixed manner.

The first clean soil distribution pilot in NYC began in the spring of 2019. East New York Farms! (ENYF) organizes youth and adults to address food justice in their community by promoting local sustainable agriculture and community-led economic development and has been working with youth, gardeners, farmers, and entrepreneurs to build a more just and sustainable community since 1998. This organization provided space for one of the initial three sites for the first pilot study of the Clean Soil Bank (Egendorf et al., 2018), and after growing crops in the soils for several years, they applied for funding from the NY State Department of Environmental Conservation to experiment with constructing and distributing these soils. The Mayor's OER supported ENYF in receiving access to a vacant lot, where they received large volumes of sediments from OER's Clean Soil Bank program, received large volumes of compost from DSNY, and have since distributed these soils by trucks to 15 local gardens, and numerous free clean soil pickup and soil testing events. Working in partnership with researchers and impacted community members, data gathered on both the microscale soil properties, and the meso- and macroscale data on efficacy of distribution will inform subsequent efforts.

5.3. Macroscale applied and participatory experiments: Connecting with other cities, legislative efforts, and the NYC Clean Soil Bank stockpile

The fact that soil Pb is not considered a primary exposure pathway is a positive feedback that leads to outcomes in which contaminated surface soils are left in situ, such that they remain potential sources of exposure (**Figure 1**). The fact that the populations most affected by contaminated soils may also lack access to structural power is another positive feedback (**Figure 3**). Although data on soil Pb and BLLs have been correlated in other cities, such research has not been conducted in NYC. What data are needed in order to understand potential risks? What data are needed in order to justify primary exposure prevention, particularly through capping and covering contaminated soils? How can affected communities be co-creators of the experiments to change this system?

Addressing these questions requires macroscale collaboration between researchers in multiple cities, as well as researchers and practitioners in a variety of fields, including law, toxicology, and EJ. Scaling up these inquiries within NYC and beyond is enabling compilation of data and formulation of research questions and methods that can begin to articulate what is needed for effective intervention in multiple locations over longer periods of time. In addition to experimenting with the material and informational resources necessary for clean soil distribution, the emerging networks in NYC are engaging with local and regional policy efforts. Pb poisoning has received heightened attention, particularly since issues with Flint, MI water sources arose, and political leaders in NYC have been creating new legislation to take action on preventing Pb exposure.

The NYC City Council has proposed legislation to test and remediate contaminated soil, and the network of researchers and community advocates in Legacy Lead have provided feedback during this process. Although Pb in soil has not been considered a primary exposure pathway for many state and city health departments, Mayor de Blasio's LeadFreeNYC plan emphasizes the importance of

constructing and distributing clean soils to mitigate exposure, largely in response to the local scientific research conducted on soil Pb (i.e., Cheng et al., 2015; https://www1.nyc.gov/assets/leadfree/). To assist in these policy efforts, researchers and advocates in NYC are sharing existing data from other cities and gathering new data in NYC to understand the risks of soil Pb exposure that have not been well characterized. What is being done in NYC is only one small example that builds on the research conducted throughout the United States and throughout the world, while aiming to contribute to what is urgently needed in various scales of time and space. The framework for applied and participatory experiments being developed in NYC is being strengthened within the 20+ organizations within Legacy Lead and is continuing to expand to support the efforts of urban growers throughout the city and local region. As such, the interventions at each scale are essential for supporting and building the others.

Even with budget cuts and shutdown associated with the global coronavirus pandemic, OER was able to open their first nonprofit stockpile to store and distribute clean excavated sediments and soils for citywide use in 2020 (https://www1.nyc.gov/site/oer/safe-land/forbell-street-stockpile.page). The stockpile has the capacity to store 12,000 cubic yards of materials, where they have been mixing sediments and composts to create constructed Technosols for community gardens, farms, and municipal uses. All soils are made available free of charge. In order to limit exposure to the legacy of lead in soil, new layers must be emplaced, creating Anthrosols or Anthroposequences (Effland and Pouyat, 1997). The stockpile is enabling new soil layer emplacement at high volumes and rates that were not previously feasible. In addition to limiting Pb exposure, many of these experiments revolving around new soil construction generate multiple cobenefits associated with urban gardening and agriculture, including increased food access and fresh produce intake (Alaimo et al., 2008; Metcalf and Widener, 2011; Saha and Eckelman, 2017), food justice and food sovereignty (Alkon, 2014; Jarosz, 2014; Horst et al., 2017), a range of health benefits (McCormack et al., 2010; Van Den Berg and Custers, 2011; Clatworthy et al., 2013; Subica et al., 2015), and enhanced community well-being (Hung, 2004; Saldivar-Tanaka and Krasny, 2004; Kingsley and Townsend, 2006; Okvat and Zautra, 2011). Ecological benefits include reduced waste (Walsh et al., 2018), reduced stormwater runoff (Gittleman et al., 2017), increased biodiversity and habitat (Goddard et al., 2010; Yadav et al., 2012; McPhearson et al., 2014; Carlet et al., 2017), and greenhouse gas sequestration (Pouyat et al., 2002; Beesley, 2012; Brown et al., 2012; Vasenev et al., 2014).

Here, we have conceptualized multiple scales of multidisciplinary interactions with Pb in soil (**Figure 7a**) and interventions aimed at mitigating soil Pb exposure (**Figure 7b**). Here, we also focus on ways that interventions can be created with participation of affected communities to effectively mitigate Pb exposure (**Figure 7c**). The applied and participatory experiments underway in NYC hypothesize that constructing soil with affected communities, with strong institutional and interorganizational connections, and cooperative development of a soil distribution network will generate data to further assist in systemic experiments that effectively limit exposure to the legacy of Pb in soil. When these efforts are aligned with policy makers and researchers in other regions, the systemic changes may amplify, and feedbacks that effectively limit exposure may proliferate. Enhanced synergism and transferability of systemic changes are the ultimate goals of this framework.

6. Summary and conclusion

Given the magnitude and increasing rate of anthropogenic changes occurring within Earth systems, is urban soil Pb truly a pressing concern? Here, we reviewed decades of research indicating the pervasive presence of Pb in soil, the life-altering and life-shortening health impacts of any form of Pb exposure, the data from a variety of contexts indicating inextricable connections between soil Pb and BLLs, the environmental injustices and disproportionate burdens of exposure placed on vulnerable populations, as well as the physical, social, and policy-based feedback mechanisms perpetuating the unjust system at a variety of scales (**Figure 7a**).

We developed and applied a systems framework that traces human and nonhuman system interactions at a variety of scales, identifying inputs as historical and ongoing Pb emissions from industry, paint, and gasoline, the behavior of Pb in soil and human bodies, and resulting outcomes of exposure on the microscale. Lack of acknowledgment by policy makers and health departments of the particular issue with soil Pb is a positive feedback enabling this cycle of exposure to persist (**Figure 1**). We then traced mesoscale temporal and spatial changes, specifically locating seasonal variations of atmospheric Pb and BLLs, indicating contaminated soil and dust resuspension and deposition as another positive feedback mechanism perpetuating risks of exposure (**Figure 2**). On the macroscale, we identified spatial patterns of high urban soil Pb concentrations with a decreasing gradient toward the exurban areas, as well as high Pb concentrations corresponding to areas with high poverty and concentrations of people of color, aligned with a significant body of EJ research. This uneven exposure also serves as a positive feedback mechanism in that people with the greatest exposure have less access to the structural power needed to address the issue (**Figure 3**).

On the macroscale, we also suggest that this broad systems-based understanding enables us to perceive Pb in soil as a noncontiguous layer of Earth's surface that holds the memory of human industrial and capitalist activity. Although neither Pb in strata nor soil in and of itself are appropriate indicators for shifts in geologic time periods, we contend that this understanding may be of use and value toward a basic science understanding of our species-wide interactions with Earth systems, as well as our particular imbalances of resources and toxins for differently identified groups of people. This understanding may not only inform rigorous and accurate depictions of material and energetic fluxes over time but can also inform experimentation with system-wide interventions.

As we traced microscale interventions aimed at changing the bioavailability or bioaccessiblity of soil Pb (**Figure 4**) and mesoscale interventions that attempt to extract Pb from soil with plants (phytoremediation; **Figure 5**), we see the limitations of these types of approaches. Indeed, the only way to effectively mitigate exposure to soil Pb on human time scales is to remove the entire soil substrate or cover it with a new material (**Figures 6** and **7b**). With either approach, a new soil medium is required in order to maintain the ecological productivity of the area. As such, we have broadly articulated the outlines of a number of applied and participatory experiments in soil construction and distribution in NYC that attend to multidisciplinary and transdisciplinary tenets of social-ecological urban systems and participatory research. With attention to the identified feedback mechanisms of soil resuspension and impacts on marginalized populations, we are co-constructing each phase of research on constructed Technosols with affected communities and building strong local networks to interact with other researchers and practitioners on national and international stages (**Figure 7c**).

The framework outlined here enables us to understand the systems of human and soil Pb interactions, identify the interventions that have been evaluated, and experiment with applied solutions. These applied experiments (Carbon Sponge, JUST SOIL, Legacy Lead, ENYFs' soil distribution pilot, and the NYC Mayor's OER's Clean Soil Bank stockpile) and legislative endeavors are furthering efforts to address this urgent and challenging issue of environmental contamination and injustice. The systems approach for addressing Pb in soil that we describe can be applied in other locations, and collaborations will continue with researchers and practitioners in other U.S. and international cities. Perhaps most importantly, we hope this systems approach will be extended to address other environmental challenges. Consideration of multiple scales of interaction between biogeochemical, ecological, social, and political factors, and using understanding of these factors and interactions to develop participatory experiments with diverse populations, should produce more effective solutions for environmental issues ranging from water quality, to deforestation, to climate change. Many more research-based efforts are needed to address these pressing issues, and the multiscalar systems approach is one that can lend itself to the creation and proliferation of sustainable systems for all of Earth's living and nonliving components.

Data accessibility statement

All data used for this article are available from given citations. No other data set is associated.

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Author contributions

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