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A “golden moment” for soils and society presents challenges and opportunities for soil science

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Abstract

We appear to be at a shining moment for interactions between soils and society. Popular interest in soils has increased along with interests in urban gardening, carbon sequestration, recognition of the vast biodiversity in soils, and the realization that soils are a finite resource whose degradation has serious consequences. This increase in interest creates both opportunities and challenges for soil science. While there is great potential for increasing the diversity of people involved with soil science, key scientific and communication challenges need to be addressed for interactions between soils and society to be useful and productive. Here, I present case study issues on the mechanisms and limitations of carbon sequestration in soils, and the need to restore and/or create new soils for specific uses including urban agriculture and green infrastructure to illustrate the opportunities and challenges associated with new societal interest in soil science. Addressing these issues requires advances in both basic and applied science, new participatory approaches to the design, execution, and interpretation of research, collaboration with multiple disciplines, including the social sciences, and improvements in the two-way flow of information between science and society. Careful attention to these issues will attract new people to soil

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science, advance awareness of the importance of and threats to soils across the globe and produce improvements in the quality of life for diverse human populations.

Keywords

carbon, constructed Technosols, contamination, green infrastructure, lead, science communication, urban

Highlights

- General interest in and concern about soils has never been greater.
- Soil science must be careful not to "over promise" what it can do for society.
- Example topics include carbon sequestration, urban gardening, and green infrastructure.
- Advances in basic and applied soil science and communication are needed to address these topics.

1. INTRODUCTION

It is a "golden moment" for soil science. Societal interest in, and concern about, soils has never been higher. There is excitement about maximizing or increasing removal of climate-altering carbon dioxide (CO_2) from the atmosphere and storing the carbon in this CO_2 as soil organic matter that enriches the capacity of soil to support plant growth. Urban populations interested in producing their own food have developed an interest in clean, productive soils. New "nature-based solutions" to provide "ecosystem services," ranging from air and water purification, to aesthetics, to spiritual and mental health improvements, rely fundamentally on soils. The titles of popular books such as "The Soil Will Save Us" (Ohlson, 2014), "Kiss the Ground" (Tickell, 2018), "Dirt to Soil" (Brown, 2018), and "A World Without Soil" (Handelsman, 2021) reflect the scope and intensity of this new interest.

New societal interest in soils is extremely gratifying and encouraging to soil scientists. For hundreds of years, interest in soils has focused on management to increase crop production, and efforts to mitigate the negative environmental effects of that management have been active for the past 60 years. Soil degradation remains widespread, offsite impacts of intensive management on air and water are profound, and interest in soil conservation has lagged behind interest in protection of air, water, and biodiversity (Baveye, 2021; Dominati et al., 2010; Kraamwinkel et al., 2021). The recent wider societal recognition of the importance and vulnerability of soils noted above suggests that long efforts in research and education are finally paying off, creating exciting new opportunities to attract new people and funding to our discipline and to see the results of research applied to important problems.

Yet the new societal interest in and excitement about soils also creates challenges for soil science. Will we meet the expectations that are created by this interest? Can improved soil management really "save us" from the greenhouse effect caused by CO_2, N_2O, and CH_4 accumulation in the atmosphere? Will we be able to provide clean and safe soils for urban gardening and agriculture? Will nature-based features function and be resilient in the face of changing climate extremes? If societal expectations are not met, will public interest and support for funding for soil science research decrease?

In this paper, I present three case studies that illustrate the opportunities and challenges created by this golden moment in soil science. "These case studies all address themes that directly affect society and its relationships with soil. First, I will discuss soil carbon sequestration and the need to be clear about the limitations of this sequestration to management of global carbon and climate warming. Second, I will discuss managing urban soils for food production, and the challenges of guaranteeing that these soils are not producing contaminated food. Finally, I will discuss the importance of soils for green infrastructure or nature-based features and address questions about how well these features function. Throughout, I will focus on the idea that sustaining new societal interest will require some changes in the way that we conduct, interpret, and communicate our research.

2. CARBON SEQUESTRATION: WILL THE SOIL REALLY SAVE US?

A 2014 book (Ohlson, 2014), addresses "how scientists, farmers, and foodies are healing the soil to save the planet." The book highlights the potential of sequestering significant amounts of carbon in soil by restoring soil organic matter levels that have been depleted by decades and centuries of farming, erosion, and human use – a "great green hope." The idea that restoring soil carbon will improve multiple components of soil quality is well established in soil science. However, the value of this restoration for managing the global carbon cycle is less certain (Moinet et al., 2023). But this idea is novel and exciting to the general public and has created interest in soils well beyond traditional academic and agriculture communities. This interest dovetails with renewed scientific interest in soil carbon sequestration, which has stimulated a large body of new basic research with new methods and models addressing soil carbon pools, fractions, and formation (Cotrufo & Lavallee, 2022). It has also driven new practical and applied research on amendments (e.g., biochar (Lehmann et al., 2021), enhanced mineral weathering (Taylor et al., 2016), and "smart farming" techniques (Lieder & Schröter-Schlaack, 2021). Much of this research is framed by the aspiration that new soil management practices can increase soil carbon sufficiently, e.g., by 0.4% per year, to have a significant impact on atmospheric CO_2 concentrations (Martin et al., 2021).

The excitement about soil carbon sequestration to help solve global climate problems must be tempered, however, by some established principles in soil science as well as by challenges in practical soil management. Of primary importance to soil scientists are ideas about equilibrium levels of organic matter and carbon sequestration (Six et al., 2002; Stewart et al., 2007; Georgiou et al., 2022). These ideas posit that there may be limits to the amount of carbon that soils can hold. Long-term data from experiments in North America (Morrow Plots, Illinois established in 1876 and Sanborn Field, Missouri established in 1888) and Great Britain (Rothamsted, established 1843) clearly show this "equilibrium effect" in both declining and aggrading phases (Figure 1). Data from the Morrow and Sanborn plots show that as grassland ecosystem soils were converted to row-crop agriculture, there was a rapid decline in organic matter levels due to removal of carbon by harvest and stimulation of decomposition due to tillage and changes in organic matter quality, followed by establishment of a new, stable, equilibrium level of organic matter. Data from the Rothamsted plots show that organic matter levels in soils that have been farmed for many years can be increased by large additions of manure, but that this increase may be finite and leads to a new, stable, equilibrium level of organic matter. These levels are controlled by soil physical and chemical conditions that protect organic matter from degradation by microbes (Six et al. 2002). While we have to be cautious about how much insight can be drawn from these two long-term study sites, soil scientists should be clear about the idea that there are limits to soil organic matter levels when we talk to general audiences about the potential for soil carbon sequestration.

There is debate about the limits to soil carbon storage. Recent analysis of a wide range of German agricultural soils (Begill et al., 2023) found no upper limit of mineral-associated organic carbon. These were methodological and interpretation concerns about these results (Cotrufo et al. 2023), and the analysis was restricted to agricultural soils and did not include natural reference sites that might represent an upper limit of carbon storage. While it is undeniable that many agricultural soils are depleted in soil carbon, and that there is potential to sequester significant amounts of carbon in these soils, realizing this potential depends on agricultural management practices and constraints (Poulton et al., 2018; Soussana et al., 2019), and there may well be a limit on the amount of carbon that can be sequestered in any given soil.

In addition to concepts about carbon saturation and equilibrium, soil scientists need to be clear with general audiences about the permanence of carbon sequestered in soil (Dynarski et al., 2020). If management that is changed to foster carbon sequestration is changed back to more conventional management, the carbon that had been sequestered can be very rapidly released back to the atmosphere. This type of dynamic was seen in the Conservation Reserve Program in the U.S. where more than 1 million ha of marginal croplands were converted to perennial grasslands between 1985 and 2005 to reduce erosion. While some of these lands accumulated carbon as grasslands, if and when they were converted back to croplands, that carbon was often lost, either to erosion or released back to the atmosphere via microbial oxidation (Abraha et al., 2018; Bowman & Anderson, 2002). These uncertainties about the permanence or reliability of soil carbon sequestration need to be considered when comparing soil-based approaches for addressing greenhouse gas-driven climate change with other approaches such as decarbonization of the economy.

An additional consideration that must be addressed with carbon sequestration, and other topics at the interface between science and society, is uncertainty. Quantifying carbon stocks of soils at specific sites, extrapolating measured values to larger (field, landscape) scales, predicting changes with models, and quantifying values of sequestered carbon are all complex and highly uncertain tasks. New approaches to characterizing uncertainty (Yanai et al. 2018), including meta-analysis (Beillouin et al. 2023), models, and long-term studies (Bradford et al., 2016), will help to improve the transmission of information from science to stakeholders.

While it is relatively straightforward for soil scientists to communicate concepts about the limits and permanence of soil carbon sequestration, making comparisons with other approaches to addressing greenhouse gas-driven climate change is much more challenging (Nayak et al., 2022). Yet, there is a clear need for us to "communicate with context" about these comparisons. This will require collaboration with social scientists and communication specialists and active engagement with stakeholder audiences. The risks of not communicating with context are high. If soil carbon sequestration becomes associated with efforts to address climate change that do not work, i.e, "greenwashing" (de Freitas Netto et al., 2020), or if efforts to increase sequestration raise equity issues, i.e., who benefits (and who does not benefit) when we direct funds towards soils versus public transport, housing, or alternative energy, the credibility of soil science with society could be severely damaged (Paul et al., 2023; Vass et al., 2013).

3. URBAN SOILS AND FOOD PRODUCTION: ARE SOILS IN THE CITY SAFE?

One of the most exciting areas in the recent golden age of soil science has been urban soils (O'Riordan et al., 2021). As with carbon sequestration, this topic has stimulated advances in both basic and applied research, as well as a strong need for “communication with context” and a risk of damaging the credibility of soil science with society.

Analysis of urban soils has motivated the development of new concepts, tools, and methods for soil description and classification. For decades, soils in cities were unmapped or mapped simply as “urban land.” However, recognition of the functional importance of urban soils led to efforts to characterize anthropogenic parent materials and soil-forming processes (Effland & Pouyat, 1997; Rossiter, 2007). These efforts have been fundamental to practical evaluation of the potential of urban soils to function as sources of pollution and to support a wide range of ecosystem services, from carbon sequestration to water purification, capture of runoff, support of green infrastructure, and food production.

Advances in urban soil science have coincided with an increase in interest in urban agriculture and food production (Wortman & Lovell, 2013). The benefits of urban food production include improvements in food security, mental and physical health, community cohesion, and provision of green space (Ilieva et al., 2022). There are active efforts to increase urban gardening and agriculture across the world (Yan et al., 2022).

Urban food production has risks and potential drawbacks, however. Soil contamination, especially with heavy metals, creates risks to producers and consumers of urban food, and there are concerns about water and air pollution associated with fertilizer, pesticide, and water use in urban soils (Wortman & Lovell, 2013). More generally, there is a need to evaluate food production spaces in the broader context of green infrastructure within cities (Evans et al., 2022). Soil scientists need to help develop and implement soil testing programs and to communicate these risks so that participation in a potentially beneficial activity (gardening) does not have negative effects on human health, environmental quality, and the credibility of scientists and policy makers.

3.1 Urban food production in New York City

New York City is an excellent case study illustrating how interest in urban food production has developed and grown in cities across the world, how concerns about the risks of this food production can be addressed, and the implications of not addressing these risks in a comprehensive way. Interest in community gardens in New York City increased in the 1970s during an economic downturn that created a large number of vacant lots (Campbell, 2017; New York City Department of Parks and Recreation, 2023). Community groups began to use these lots for gardening, and the lots became focal points for community cohesion and the other benefits of urban food production. Improvements in the economy that increased pressure to develop vacant lots drove efforts to conserve and protect garden spaces. The New York City “Green Thumb” program now includes 550 gardens and 20,000 garden members and provides more than 40 ha of public open space (New York City Department of Parks and Recreation, 2023).

As interest in urban food production increased around the world, soil scientists played an important role raising concerns about soil contamination. In New York City, an urban soil lab at Brooklyn College of the City University of New York encouraged gardeners to send in soil samples for analysis. This program revealed widespread contamination of soils across New York City (Cheng et al., 2015) and motivated extensive research and extension efforts, e.g., the Cornell University Healthy Soils, Healthy Communities program, to provide science-based information about soil contaminants and healthy gardening practices to urban food producers (https://blogs.cornell.edu/healthysoils/). These efforts have produced and disseminated best practices for healthy gardening that include the use of raised beds, testing of soil and compost materials, and handling of produce and soil to avoid exposure to contaminants.

Still, challenges remain. For example, in 2014 a local tabloid newspaper in New York City (New York Post) published an article entitled "Root of all evil: Vegetables in NYC gardens are toxic" based on incomplete and inaccurate interpretation of a scientific paper (McBride et al., 2014). This article created great concern in the urban gardening community and highlights the challenges of societal interest in soil science and the need for soil scientists to redouble their efforts to "communicate with context" about the actual and perceived risks of urban food production (Paltseva et al., 2020; Paltseva et al., 2022). Failure to meet this challenge could result in negative effects on human health, environmental quality, and the credibility of scientists and policy makers.

One promising approach is to carry out community-based, participatory research where research questions and projects are jointly defined, and results are interpreted, by scientists and community members working together (Wadoux & McBratney, 2023). Participatory efforts have been used to engage with indigenous and traditional food producers (Kerr et al., 2007) and they have also been used to engage with farmers in the U.S. and Europe (Mason et al., 2024; Snapp et al., 2019; Stoate et al., 2019). A participatory approach could produce information on both actual and perceived levels of contamination, both of which are critical for maintaining or increasing participation in urban food production. Other challenges in this area include emerging contaminants such as plastics and per- and polyfluorinated substances (PFAS), i.e., "forever chemicals." There is a clear need for dynamic and participatory research on these developing threats to the safety of urban food production. It is not clear, however, how participatory research will be developed. Who will pay for these programs? How will their effectiveness be evaluated? How will participants be rewarded and a workforce developed and recruited? Interest in participatory research is active in many disciplines, and soil scientists have high potential to collaborate with these disciplines to make progress in this important development.

3.2 Constructed Technosols as a solution to urban (and other) soil challenges

The need to create raised beds for urban agriculture has stimulated interest in constructed soils, or "Technosols" (Deeb et al., 2020; Schad, 2018). Interest in Technosols is driven by multiple factors, including the use and/or recycling of various urban waste materials (Rodríguez-Espinosa et al., 2021). For urban agriculture, interest in Technosols is constrained by the need for uncontaminated materials (Séré et al., 2021). In New York City, a "Clean Soil Bank" program was developed that involved the use of clean fill excavated from construction sites and mixed with compost to create Technosols for community gardens across the city (Egendorf et al., 2018; Egendorf et al., 2021). Certain areas of New York City are developed on deposits of fine-sandy glacial outwash that makes an excellent soil material when mixed with compost. The Clean Soil Bank program has reduced disposal costs for real estate developers, truck traffic (3.5 million km) and greenhouse gas emissions (4,800 metric tons of CO_2) associated with disposal. The program also produced a large volume of clean soil material (544,000 metric tons) for urban food production (New York City Office of Environmental Remediation, 2024).

The Clean Soil Bank program is an excellent example of how and why interest in soils has increased in society. It has stimulated interest in Technosols for multiple purposes across the world and created a need for basic and applied research to determine the suitability of constructed soils for these purposes (Deeb et al., 2020). Will physical, chemical, and biological properties of Clean Soil Bank soils develop over time to sustain plant productivity? A major issue that has emerged is the need for sources of clean compost to mix with geologic materials to create soils that are safe for food production. Urban composts can have high levels of lead (Egendorf et al., 2018, Figure 2), and there is great uncertainty about the sources of this lead. There is a clear need for research on urban composting programs to address this issue. Another issue is the availability of suitable geologic materials for Technosols in different cities (Wortman et al. 2013). This likely varies with inherent geologic conditions and raises ideas about mapping or predicting "soil sheds" in different regions. There is also interest in using waste materials in Technosols, but research is needed to determine what kinds of waste materials can be used for different purposes in different places (Deeb et al., 2020).

Answering these questions could facilitate expansion of urban food production, and the benefits it brings, in many areas. These questions must be addressed in ways that facilitate participation and communication with multiple societal groups (Wadoux & McBratney, 2023). We are well aware of the need to scientifically determine if soils are safe for different uses. What is harder, and equally important, is to determine if different stakeholders believe that their soils are safe and how we can help these stakeholders to make that assessment.

4.0. HOW DOES BROWN INFRASTRUCTURE CONTROL THE FUNCTION AND VALUE OF GREEN INFRASTRUCTURE?

The development of green infrastructure to capture stormwater runoff and provide a wide range of ancillary benefits has been one of the most exciting topics in urban environmental science over the past 30 years. There has always been recognition of the importance of green spaces in cities to moderate the climate, provide aesthetics, and to support food production and other ecosystem services (Wang & Banzhaf, 2018). In recent decades, regulatory structures have emerged to allow green infrastructure features to be used to meet standards for stormwater management (Grabowski et al., 2022). This emergence has stimulated a burst of creative activity to design and construct features that include engineered and more natural components to capture stormwater while still providing the more traditional benefits of urban green spaces.

Soils are the fundamental "brown" infrastructure that underlies the performance of green infrastructure (Montgomery et al., 2016). Their properties control infiltration of stormwater and the growth of plants that provide ancillary benefits. There are significant uncertainties related to this support, however. Conditions in many green infrastructure features can be extreme, e.g., high air and water temperatures associated with impervious surfaces, foot traffic, and direct human disturbance of soil and vegetation. Urban street runoff can be very hot, and can have high concentrations of salts, hydrocarbons and other contaminants that can degrade the function of soils and vegetation in these features. Over time, contaminants, especially metals such as lead, will accumulate in soils, potentially affecting biogeochemical functions that influence pollutant absorption and plant growth (Deeb et al., 2020; Deeb et al., 2018; Taguchi et al., 2020). Research in New York City by Deeb et al. (2018) found that soils in green infrastructure features that were closely connected to street runoff had higher levels of contaminants (lead, petroleum hydrocarbons) (Figure 3). However, this accumulation did not appear to be having negative effects on soil biogeochemical functions related to water quality such as denitrification (Deeb et al., 2018). Further research is needed on interactions between green infrastructure feature designs and the contamination and function of the brown infrastructure that is central to them.

An even greater challenge is maintenance of green infrastructure features. Accumulation of trash and physical disturbance can affect hydrologic, soil, and vegetation conditions as well as the function of these features. Responsibility for their maintenance must be clearly established by municipal authorities and affords an opportunity for new jobs related to green infrastructure.

There are also concerns about equity in the placement of green infrastructure, as there is great variation in enthusiasm for green infrastructure solutions within and between cities. These differences lead to concerns about spending money and utilizing space in one (potentially poor) neighborhood that produces downstream benefits in other (potentially rich) neighborhoods (Grabowski et al., 2023; Hager et al., 2013; Hoover et al., 2021) (Figure 4).

The complications of green infrastructure are an excellent example of the opportunities and challenges of our current golden age of soil science. There is great enthusiasm about the importance of soils in green infrastructure and other "natural and nature-based" features (Wijsman et al., 2021). But if these features fail to deliver promised benefits, or if they create equity issues, the credibility of our discipline will decrease

Soil scientists need to be clear about the scientific limits and uncertainties about soil processes in green infrastructure features. As for urban food production, a community-based, participatory approach would be useful for these efforts. There is a clear need for information on both the actual and perceived levels of the ability of these features to provide a range of ecosystem services, and a participatory approach has the potential to produce this information.

5.0 CONCLUSIONS

The current golden age of soil science has the potential to produce many benefits for our discipline. It will allow us to attract new students with diverse backgrounds, to expand the scope of our work into new questions and applications, and to attract funding and attention for our research. The solutions to many pressing societal problems, from climate change to urban food production, involve soils, and it is gratifying and exciting to see new societal interest in our discipline.

Sustaining new societal interest will require some changes in the way that we conduct, interpret, and communicate our research. As societal interest in our work increases, we need to take a more participatory approach to defining questions, designing studies, and interpreting our results. There is a strong need to "communicate with context" so that results can be kept in proper perspective and concerns about "over promising" and equity can be clearly addressed. If we do not accept the challenges inherent in new societal interest, the benefits associated with this interest will not persist.

Participatory approaches and improvements in science communication are developing in many scientific disciplines (Zoellick et al., 2012). New societal interest creates an opportunity for soil scientists to be leaders in this development. This would be exciting and appropriate for a discipline that has a long history of contributing to human well-being through its contributions to food production and environmental quality. Now we have an opportunity to use this history to expand the scope of our impact, and to help influence the development of other disciplines.

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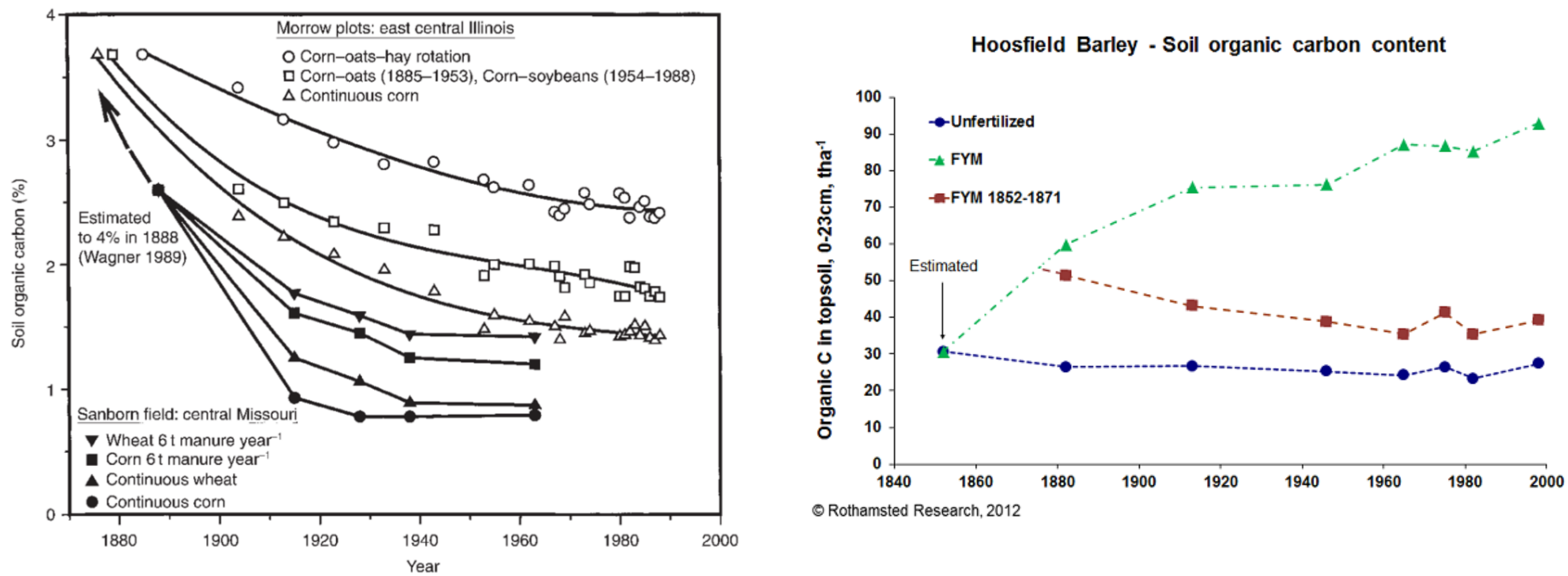

Figure 1. Soil organic carbon contents of selected treatments of (left) the Morrow plots at the University of Illinois and Sanborn field at the University of Missouri (from Reicosky et al., 2000) and (right) the classical Hoosfield experiment at Rothamstead Experiment Station in England (Rothamsted Research, 2012).

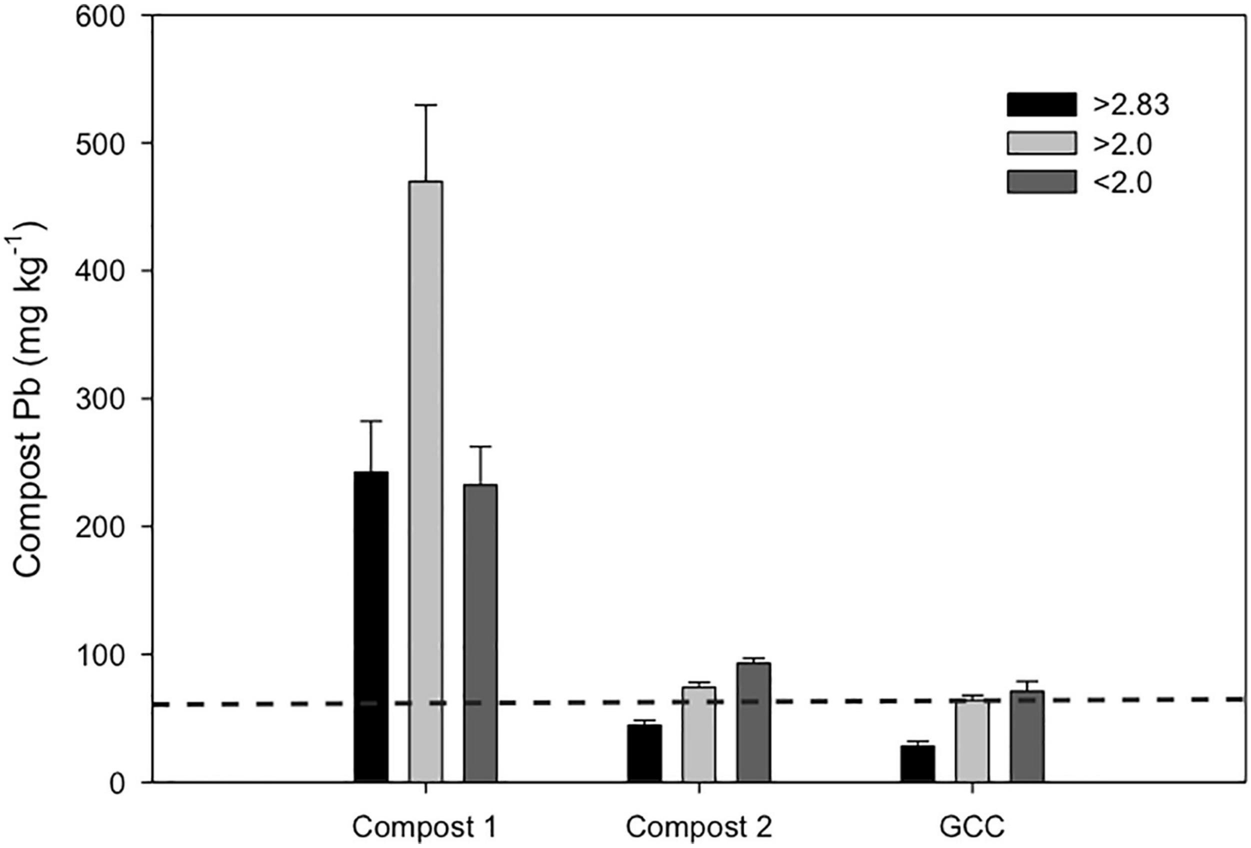

Figure 2. Mean ± SE (n=6) Pb concentration in three size fractions (> 2.83 mm, 2.0–2.83 mm,<2.0 mm) of the three different composts considered for mixing with Clean Soil Bank sediments in New York City, NY USA. Dashed horizontal line represents NYS Department of Environmental Conservation Soil Cleanup Objectives Unrestricted Use (SCOUU) criteria for Pb. From Egendorf et al. (2018).

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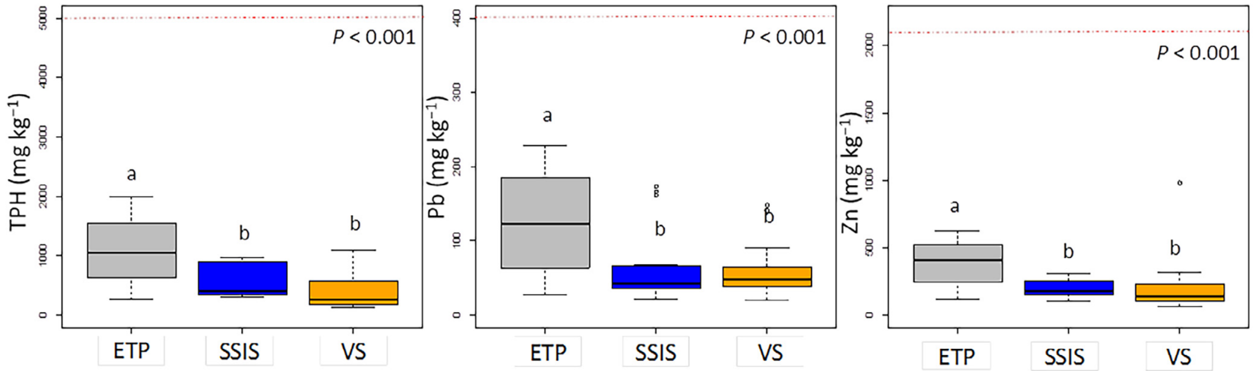

Figure 3. Boxplots showing the effect of green infrastructure designs in New York City (enhanced tree pits (ETP), street-side infiltration swales (SSIS), and vegetation swale (VS)), on the concentrations of total petroleum hydrocarbons (TPH), lead (Pb) and zinc (Zn), respectively. The middle bar is the median, the box extends from the 25% to the 75% quartile, and horizontal bars show minimum and maximum values. Significant differences ($P < 0.05$) are indicated by different letters. Dashed line is the European soil contamination threshold. (n=12, 15, 33 for ETP, SSIS, and VS, respectively). The level of "connectivity" to the street is ETP > SSIS > VS. From Deeb et al. (2018).

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Figure 4. A green infrastructure feature in a neighborhood in Baltimore, MD, USA. This feature is designed to reduce runoff to receiving waters in areas outside this neighborhood, which has issues with vacant housing and other societal problems. The feature has accumulated trash,

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despite a “please don’t litter” sign and planted vegetation has been disturbed. From Groffman et al. (2023).