frontiers in Environmental Science

EDITORIAL
published: 06 January 2022
doi: 10.3389/fenvs.2021.830337

Editorial: Searching for Solutions to Soil Pollution: Underlying Soil-Contaminant Interactions and Development of Innovative Land Remediation and Reclamation Techniques

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Keywords: bioremediation, phytoremediation, bioavailability, organic pollutants, emerging pollutants

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†This Research Topic is dedicated to the memory of Petra Susan Kidd, brilliant scientist, extraordinary woman, and great friend, who passed away prematurely on January 2, 2020, after she contributed enthusiastically to the launch of this Research Topic

Specialty section:
This article was submitted to Soil Processes, a section of the journal Frontiers in Environmental Science

Received: *07 December 2021*
Accepted: *16 December 2021*
Published: *06 January 2022*

Citation:
Monterroso C, Balseiro-Romero M, Garbisu C, Kidd PS, Qafoku NP and Baveye PC (2022) Editorial: Searching for Solutions to Soil Pollution: Underlying Soil-Contaminant Interactions and Development of Innovative Land Remediation and Reclamation Techniques. Front. Environ. Sci. 9:830337. doi: 10.3389/fenvs.2021.830337

Editorial on the Research Topic

Searching for Solutions to Soil Pollution: Underlying Soil-Contaminant Interactions and Development of Innovative Land Remediation and Reclamation Techniques

Soils are complex and dynamic systems that perform essential functions contributing to the sustainability of terrestrial ecosystems and the support of life. They participate in a wide variety of ecosystem functions/services (e.g., Baveye et al., 2016), including those related to the production of biomass, the regulation of carbon and nutrient cycles, and the regulation of water resources and air quality, due to their filtering and buffering capacity.

Over the last decades, increasing industrialization, urbanization, intensive agriculture, and mining operations have resulted in the release of significant amounts of contaminants into soils, markedly affecting soil functionality and ecosystem services (e.g., Qafoku et al., 2010; Rodríguez Eugenio et al., 2018; Balseiro-Romero and Baveye, 2018). Contaminated soils can negatively affect water and air quality, vegetation and food quality, and human health. There are many potential soil contaminants, including heavy metals or trace elements (e.g., lead, cadmium, chromium, cobalt, copper, mercury, nickel, and zinc), petroleum hydrocarbons, and persistent organic pollutants (e.g., pesticides, polycyclic aromatic hydrocarbons, polychlorinated biphenyls, furans, and dioxins). In addition, in recent years, emerging contaminants (e.g., personal care products and pharmaceutical products, such as hormonal compounds and antibiotics, nanoparticles) and biological contaminants (viral and bacterial pathogens) have also raised significant concern. The effect of climate change variables (Qafoku, 2015) and/or CO_2 sequestration and storage activities (Shao et al., 2016) on the release of contaminants affecting soil water quality has also been the subject of research and has attracted the interest of researchers and decision makers.

Although many research efforts have been, and are being, devoted to the recovery of soil functionality through the application of a variety of soil reclamation and remediation procedures, there is still much need for additional work in this important area. Soils are highly complex systems, and their remediation or reclamation must be adapted to the specific land properties and use, the environmental conditions and the (mix of) pollutants present, a list that is continuously growing along with the "progress" of society. There is an urgent imperative to understand the interaction of pollutants with soil components, and their influence on microbial activity and biodiversity, which play an essential role in the recovery of degraded lands. Also, it is urgent to develop innovative, less-destructive land remediation and reclamation procedures, avoiding traditional methods that may cause loss of soil functionality. Indeed, practical experience has shown that in many situations, excavation, as well as thermal-, or chemical treatments often negatively affect the biodiversity and architecture of soils.

In this general context, this Research Topic (RT) was launched with the explicit aim to bring together articles describing innovative advances in soil pollution research, focusing on, but not limited to 1) risk assessment and contaminated land management based on soil use and/or contaminant bioavailability, 2) innovative soil reclamation procedures and/or remediation techniques such as biologically based technologies, nanoremediation, organic matter additions and organic based amendments, and emerging sorbents, 3) best-performing and emerging parameters and indicators to monitor soil quality during and after application of remediation techniques, 4) emerging contaminants and risks associated with reusing treated wastewater, sewage sludge or livestock residues improperly treated, as a main source of biological pollutants or antibiotic residues, related to the presence of antimicrobial resistant bacteria in soils, 5) modelling the impacts of soil pollution on food, water and air quality, public health, and ecosystem services, 6) presence and effects of co-contaminants (complex mixtures of pollutants, commonly present in brownfields, but also in other contaminated sites; effects on microbial activity and diversity), and finally 7) field case-studies of successful management and remediation of polluted soils.

Of the six contributions that make up this RT, two are Original Research Articles and four are Reviews. One research article, by Shi et al. deals with the characterization of the status of contaminants in soils, and with how it is affected by the interactions between these contaminants and the heterogeneous soil matrix. One research article, by Guo et al., deals with the addition to soils of extraneous materials, in their case pyrolyzed organic matter (the so-called "biochars"), to remediate the soils by scavenging contaminants. The review articles all deal with strategies that rely on biological systems, either through phytoremediation (Zapata-Carbonell et al.; Moreira et al.), bioremediation (Wallis et al.) or a combination of the two (Alkorta and Garbisu) to achieve satisfactory levels of remediation or reclamation of contaminated soils. In the following, we shall briefly outline the key contributions of these different articles.

In virtually all countries, the total concentration of contaminants in soil is used to establish regulatory guidelines for environmental risk assessment, contaminated land management, and policy decisions. For at least 2 decades, various authors have recommended the use of a bioavailability approach instead in soil regulations, on the grounds that total contents overestimate potential environmental risks, and that it is the bioavailability of contaminants that determines the progress of bio-based soil remediation strategies (e.g., Kördel et al., 2013). A key obstacle for regulations to move in that direction is that it has proven so far impossible to come up with a standard, theoretical concept of bioavailability, and that it is still usually defined only operationally by bioassays with plants/animals and/or indirect (one-step or sequential) chemical extractions (e.g., Ortega-Calvo et al., 2015). Bioavailability is affected by soil properties (pH, Eh, clay, organic matter, etc.), pollutant properties (polarity, oxidation states, acidity, etc.), biotic factors (target organisms/organ, age, etc.), and environmental factors (hydrology, climatic conditions, etc.). These properties are dynamic in time and place. Thus, it is important to understand the limitations of determinations of operationally-defined bioavailability and that further studies on key factors and mechanisms controlling the potential mobility and bioavailability of soil pollutants are necessary. In this respect, the article of Shi et al. focuses on the effect of soil composition and temperature on the sorption/desorption of naphthalene and benzene, two representative aromatic petroleum hydrocarbon (PHC) compounds. They observe that even in simple artificial soil systems, temperature variations can have complex, but predictable, effects on the soil-water partitioning of PHC contaminants and, hence, on their mobility and bioavailability. According to the authors, understanding the role of temperature is a prerequisite to unraveling the coupled abiotic and biotic processes that modulate the fate of PHC in real-world soils.

Part of the difficulties encountered in research on the bioavailability of organic contaminants, and in the development of suitable reclamation/bioremediation strategies, is the fact that contamination by organic compounds rarely occurs in isolation, and in practice is often accompanied by the presence of inorganic pollutants. The latter can negatively affect the activity and metabolism of microorganisms that degrade organic contaminants. One way to alleviate the health risks associated with contaminants as well as their toxic effects on microorganisms is to use sorbents to remove inorganic contaminants from soil solution. The idea of adding extraneous solids to soils to facilitate their ultimate remediation was advocated initially a decade ago and continues to be advocated today especially in using commonly occurring Fe oxides nanoparticles for remediation purposes (Wang et al., 2020). Recently, various authors have argued for the use of pyrolyzed organic residues (referred to as "biochars") as contaminant scavengers in soils (Uchimya et al., 2011; Jiang et al., 2012; Xu et al., 2016). Biochars have been the object of widespread attention over the past 15 years, but have also given rise to significant criticism (e.g., discussion in Baveye, 2021), mainly because many aspects of their use as soil amendments remain controversial and poorly understood, including possible health risks, which have yet to be fully investigated.

In that context, the review article of Guo et al. summarizes findings on the processes, mechanisms, and effectiveness of biochar as a contaminant scavenger in soils. These authors emphasize that biochar products derived from different sources show different capacities and efficiencies to stabilize soil contaminants. Inorganic cationic contaminants such as

Cd, Cu, Ni, Pb, and Zn are immobilized *via* adsorption and precipitation, influenced by the cation exchange capacity, pH, and ash content of biochars. On the other hand, biochar amendments increase the mobility of toxic, anionic elements (e.g., Cr, As, and Sb) in soils. However, the increased partitioning of anions into solution could facilitate their phytoextraction-based remediation in vadose zone soils but could also negatively increase their leaching to aquifers. Non-polar organic compounds are also immobilized, a process controlled by such factors as biochar specific surface area, microporosity, and hydrophobicity. Guo et al. point out that the presence of biochar may stimulate microbial activity facilitating organic contaminant degradation. Additional research is needed, especially concerning the long-term effectiveness of remediation in biochar-amended soils.

Over the last 2 decades, rather than face uphill battles with regulators over the suitability of adding solids like biochars or engineered nanoparticles to contaminated soils to make inorganic contaminants less toxic, researchers have favored a number of alternative strategies. These involve either the plant-based extraction of heavy metals from soil (using plants with the capacity to accumulate high concentrations of heavy metals in their aboveground tissues, i.e. the so-called phytoextraction with hyperaccumulators) or through their immobilization in the roots *via* phytostabilization strategies aimed at decreasing metal mobility, bioavailability and, hence, ecotoxicity.

Unfortunately, the use of phytoremediation strategies to clean up metal contaminated soils suffers from a number of limitations as well, which are hampering and even discouraging its commercial application. Regarding phytoextraction, the most critical drawback of this technology is the great deal of time required to effectively extract heavy metals from the soil (in many cases, many decades are needed to successfully do so), a fact that understandably dissuades soil managers and remediation companies from using this strategy. Certainly, the small biomass and slow growth of many hyperaccumulators have negatively affected the effectiveness of many phytoextraction initiatives, bringing up the necessity to explore possibilities for stimulating plant growth and heavy metal uptake during phytoextraction, such as, for instance, the inoculation of plant growth-promoting bacteria (Burges et al., 2017). On the other hand, phytostabilization has an important legal obstacle, namely, the fact that environmental legislations are normally based on total metal concentrations, which invalidates the usefulness of this phytotechnology from a regulatory perspective. Besides, although the application of phytostabilization strategies can indeed reduce bioavailable metal concentrations in soil, there is always the possibility that, later, the immobilized heavy metals are again mobilized due to changes in soil conditions. In consequence, one must at all times be cautious against this possible reversal of soil metal immobilization (Alkorta et al., 2010). It is essential in this respect to establish long-term follow-up monitoring programs (Epelde et al., 2014) with a concomitant increase in economic costs.

Given these constraints for the effective application of phytoremediation initiatives under real case scenarios, a lot of emphasis has been put in the last few years on phytomanagement, a most promising phytotechnology based on the utilization of plants to control contaminant linkages, while providing economic revenues (*via* the generation of non-food crops for biomass-processing technologies from the biofuel and bioenergy sector, ecomaterials, biosourced-chemistry, etc.) and ecosystem services. The phytomanagement paradigm promotes the establishment of plants with phytoremediation potential as part of an integrated site management that pursues the accomplishment of economic, social and environmental benefits. This possibility of obtaining co-benefits (products and ecosystem services) while dealing with metal contamination-derived risks, makes site remediation a much more attractive option for stakeholders. Interestingly, phytomanagement has been proposed as an attractive "holding strategy" until full site regeneration is possible.

Along this line of thought, Moreira et al. present a comprehensive review of the many options currently available for the phytomanagement of metal(loid)-contaminated soils, while discussing their corresponding efficiency and associated values. These authors emphasize that phytomanagement closely relies on the suitable selection of plants, as well as of microbial inoculants (mycorrhizal fungi and plant growth-promoting rhizobacteria and endophytes) with the ability to behave as powerful plant allies. In particular, the review paper by Moreira et al. provides an exhaustive overview of the main annual, perennial and woody crops currently used in phytomanagement, and highlights the future opportunities of phytomanagement for stakeholders and end-users.

As a practical example of this phytomanagement approach, Zapata-Carbonell et al. deal with the revegetation of residual red gypsum tailings, focusing on Mn phytoextraction by silver birch to render the operations economically profitable through the potential use of such phytoextracted raw material for the production of ecocatalysts. Interestingly, the authors applied a variety of amendments (i.e., pine bark chips, Miscanthus straw, white peat, and ericaceous compost) to decrease pH in an attempt to enhance nutrient availability from the residual red gypsum tailings, finding out that the application of ericaceous compost resulted in an adequate plant development and biomass production, and a higher leaf Mn removal per plant.

In-situ or *ex-situ* bioremediation, involving bacteria and/or fungi, is well established as a strategy to clean up contaminated subsurface environments. It has so far focused on the biodegradation of organic contaminants, *via* biostimulation and bioaugmentation strategies, with special attention to petroleum hydrocarbons, chlorinated- and other recalcitrant compounds. However, in nature, biologically-mediated processes also are capable of enhancing the weathering of minerals (such as in bioweathering). Therefore, bioremediation of soils contaminated with mineral substances is worth exploring as an alternative or complement to other techniques to deal with inorganic pollutants. In this context, Wallis et al. address the challenge of detoxifying asbestos-contaminated waste and soils, a worldwide environmental problem, through a bioremediation system. These authors outline evidence pointing to the ability of microbial and plant communities to remove from asbestos the iron that contributes to its carcinogenicity. These observations open up the prospect, in particular, of creating ecosystems over

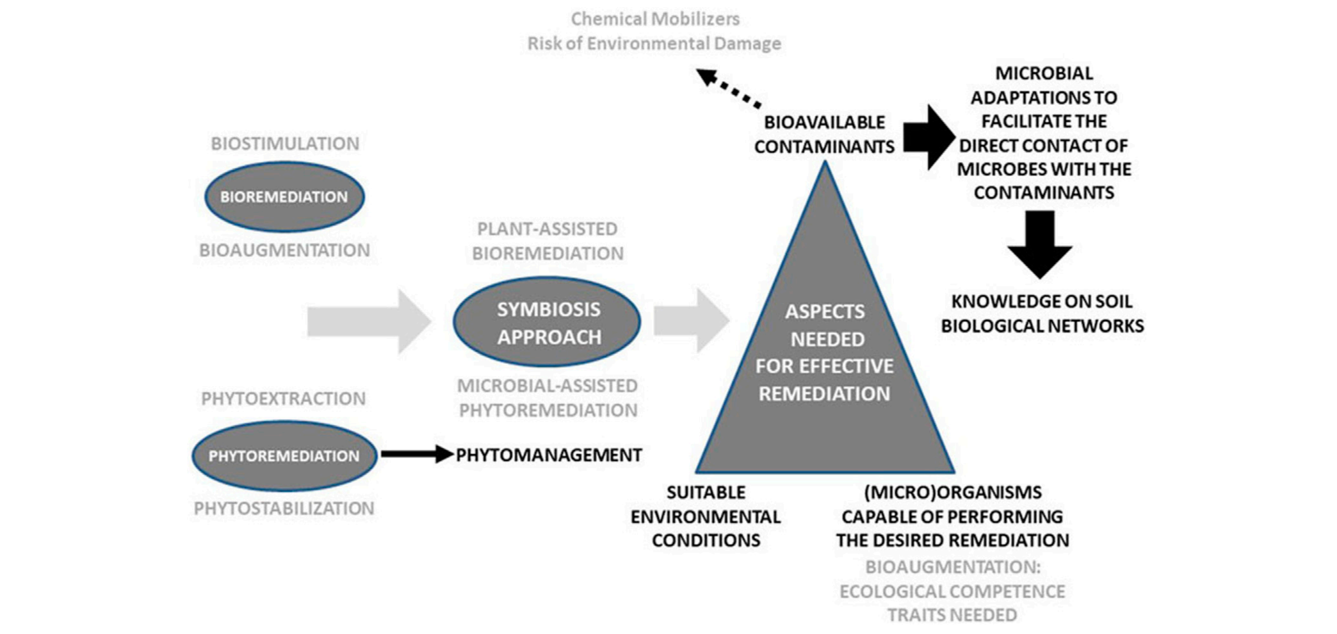

FIGURE 1 | Schematic illustration of the recent integration of two traditionally distinct remediation approaches into a "symbiotic" approach, and resulting research needs that have to be addressed in the future (Reprinted from Alkorta and Garbisu).

asbestos landfills ("activated landfills") that utilize nature's chelating ability to degrade this toxic product effectively.

The fact that only one of the articles in this RT deals with the characterization of the status of contaminants in soils may suggest to casual readers that most everything about this topic is known at this stage, and that the various reclamation or remediation strategies described in this RT are based on very solid conceptual and experimental foundations. The opposite is probably closer to the truth, unfortunately. Several authors who contributed to this RT argue strongly that fundamental research is needed to better understand the processes underlying the bioremediation or phytoremediation of contaminated soils. The bioavailability of organic contaminants is a case in point in this respect. Unless we grasp far better than we do now what controls this parameter, any hope of making bioremediation systematically work in practice seems unwarranted. Fortunately, technological advances over the last 2 decades (e.g., Baveye et al., 2018; Baveye et al., 2022; Vogel et al., 2021) as well as significant progress in terms of mathematical modelling (e.g., Pot et al., 2021) enable us at present to study at the micrometric scale typical of bacteria and archaea the array of processes that are likely to control the bioavailability of organic contaminants, as well as the release by microorganisms of sorbed inorganic compounds (e.g., Jacobson and Baveye, 2004).

The increased knowledge that will result from these research efforts will be particularly useful in years to come as we further explore innovative strategies for the clean-up of polluted subsurface environments. Especially exciting in this respect, as outlined by Alkorta and Garbisu, are strategies that attempt to combine the advantages of bioremediation and phytoremediation (**Figure 1**). Microbially-assisted phytoremediation deals with the inoculation of plant growth-promoting microorganisms to improve phytoremediation efficiency (e.g., Balseiro-Romero et al., 2016; Balseiro-Romero et al., 2017). Similarly, plant-assisted bioremediation involves the stimulatory effect of plant growth on the microbial degradation of soil contaminants (e.g., Rodríguez-Garrido et al., 2020). The combination of plants and microorganisms is nowadays often recommended for mixed contaminated soils. Phytomanagement has emerged as a phytotechnology focused on the use of plants and associated microorganisms to decrease contaminant linkages, maximize ecosystem services, and provide economic revenues. The potential of these relatively new, "symbiotic" methods seems very promising. However, as is pointed out repeatedly in this RT, much more research is needed to make the most of the many ways that microorganisms have evolutionary developed to access the contaminants, and to better understand the soil microbial networks responsible, to a great extent, for soil functioning.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

ACKNOWLEDGMENTS

We would like to express our sincere gratitude to the various reviewers who very generously volunteered their time to help the authors improve their texts.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.